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Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation

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PREFACE

The University of Texas at San Antonio (UTSA) is a relatively new university. It was established in 1969 and opened for classes in 1973. As the only comprehensive public university serving the nation's ninth largest city, it was and is vital to San Antonio and the entire South Texas Region. In 1982, just eight years ago, an undergraduate engineering program was established at UTSA with the support of the community and its leaders. Today, all three undergraduate engineering programs are ABET accredited and serve about 800 students, a significant percentage of whom are Hispanic. The future includes a new engineering building, containing laboratory facilities and equipment, planned to open in January, 1991. Furthermore, a graduate program has just been put in place at the M.S. level and one is planned at the Ph.D. level. The first Master's Degree students enrolled in Fall, 1989.

Naturally, the engineering research environment is just developing at UTSA. Now, thanks in great measure to the UT System support and this ongoing NASA grant, good progress is being made. Specifically, the purchase of a UT System Cray-X-MP in March, 1986 and a second one in December, 1988 has provided a world-class analytical and numerical research environment not ordinarily available to a new university. As a result the UTSA Supercomputer Network Research Facility (SNRF) was developed by the principal investigator, Dr. Lola Boyce. This has allowed the successful completion of this research project, an early one of its kind at UTSA.

This NASA research grant has allowed three Mechanical Engineering students, Thomas Lovelace, Callie (Scheidt) Bast and Eddie Aponte, to work directly with the principal investigator, Dr. Boyce, providing them with a quality research experience they would otherwise probably not have had. All students have expressed an interest in continuing their education at the graduate level.

In conclusion, and in view of the significant accomplishments in fundamental research, enhancement of the engineering research environment at UTSA, and direct support of Mechanical Engineering students, it is hoped that the proposed extension of this grant will receive favorable consideration at NASA. The principal investigator sincerely thanks NASA for funding this second year grant.

ABSTRACT

This report presents the results of a second year effort of a research program conducted for NASA-LeRC by The University of Texas at San Antonio (UTSA). The research included development of methodology that provides probabilistic lifetime strength of aerospace materials via computational simulation. A probabilistic phenomenological constitutive relationship, in the form of a randomized multifactor interaction equation, is postulated for strength degradation of structural components of aerospace propulsion systems subjected to a number of effects or primitive variables. These primitive variables often originate in the environment and may include stress from loading, temperature, chemical or radiation attack. Time may also interact with them, producing creep and fatigue. In most cases, strength is reduced as a result. This multifactor interaction constitutive equation is included in the computer program, PROMISS. Also included in the research is the development of methodology to calibrate the above-described constitutive equation using actual experimental materials data together with a multiple linear regression of that data, thereby predicting values for the empirical material constants for each effect or primitive variable. This methodology is included in the computer program, PROMISC. Actual experimental materials data were obtained from the open literature for a number of nickel-base superalloys and a few metal-matrix materials, materials typically of interest for aerospace propulsion system components.

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1.0 INTRODUCTION

This report presents the results of a second year effort of a research program entitled "Development of Advanced Methodologies for Probabilistic Constitutive Relationships of Material Strength Models, Phase 2." This research is sponsored by the National Aeronautics and Space Administration-Lewis Research Center (NASA-LeRC). The principal investigator is Dr. Lola Boyce, Associate Professor of Mechanical Engineering, The University of Texas at San Antonio (UTSA). The objective of the research program is the development of methodology that provides probabilistic lifetime strength of aerospace materials via computational simulation.

As part of this second year effort, a probabilistic phenomenological constitutive relationship, in the form of a randomized multifactor interaction equation, is postulated for strength degradation of structural components of aerospace propulsion systems subjected to a number of effects or primitive variables. These primitive variables often originate in the environment and may include stress from loading, temperature, chemical or radiation attack. Time may also interact with them, producing creep and fatigue. In most cases, strength is reduced as a result. Also included in the research is the development of methodology to calibrate the multifactor interaction constitutive equation using actual experimental materials data together with a multiple regression of that data, thereby predicting values for the empirical material constants for each effect or primitive variable. Section 2.0 summarizes the theoretical background for the research.

The above-described randomized multifactor interaction constitutive equation is included in the computer program, PROMISS. Calibration of the equation by multiple linear regression of the data is included in the computer program, PROMISC*. These programs were developed using the UTSA Supercomputer Network Research Facility (SNRF) Cray X-MP, completely compatible with the NASA LeRC Cray X-MP. Thus, these new versions of the programs will execute on the current NASA-LeRC supercomputer facilities. The latest versions (Ver. 2.0) of these programs are obtainable from the principal investigator at the address given on the cover page of this report. To verify program performance, several sample problems for each program accompany this report (see APPENDIX 1, Section 6.0 and APPENDIX 2, Section 6.0 and the enclosed floppy disks). IMSL Ver. 10 [1] subroutines are utilized.

Sections 3.0 through 8.0 address specific tasks described in the proposal for this research [2]. Specifically, Section 3.0 presents and discusses cases for analysis that resulted from a sensitivity study, utilizing the PROMISS "fixed" capability. The cases show the effect on probabilistic lifetime strength for each of several effects or primitive variables (quasi-static stress, mechanical fatigue, thermal fatigue and creep) at both high and low temperature conditions. Section 4.0 describes and references the complete computer documentation for both PROMISS and PROMISC, contained in this report as User Manuals (see APPENDIX 1 and APPENDIX 2). Section 5.0 describes and discusses the increased capability of PROMISS, Ver. 2.0, over the original version, Ver. 1.0, written at NASA-LeRC during the Summer of 1988. Section 6.0 describes and discusses the increased capability of PROMISC, Ver. 2.0, over the original version, Ver. 1.0, written at NASA-LeRC during the Summer of 1988. Section 7.0 describes and discusses the materials data collected from the open literature to be used in developing data for the PROMISS Resident Database. Section 8.0 discusses the precautions necessary to

*PROMISC was written and referenced as "RAMS" during the Summer of 1988 and in the proposal for this research.

combine PROMISS and PROMISC and the future research needed to consider such a combined code.

A paper was produced documenting much of the effort of this second year research program. This paper is entitled "Probabilistic Constitutive Relationships for Material Strength Degradation Models", by L. Boyce and C. C. Chamis. It was presented at the 30th Structures, Structural Dynamics and Materials Conference, Mobile, AL, April, 1989 and is published in the Proceedings. It has also been submitted to the AIAA Journal of Propulsion and Power.

2.0 THEORETICAL BACKGROUND:

PROBABILISTIC PHENOMENOLOGICAL CONSTITUTIVE RELATIONSHIP FOR LIFETIME STRENGTH OF MATERIALS

Recently, a general phenomenological constitutive relationship, for composite materials subjected to a number of diverse effects or primitive variables, has been postulated to predict mechanical and thermal material properties [3, 4, 5, 6]. The resulting multifactor interaction constitutive equations summarize composite micromechanics theory and have been used to predict material properties for a unidirectional fiber-reinforced lamina, based on the corresponding properties of the constituent materials.

These equations have been modified to predict the mechanical property of strength for one constituent material due to "n" diverse effects or primitive variables. These effects could include both time-independent and time-integrated primitive variables, such as mechanical stresses subjected to both static and impact loads, thermal stresses due to temperature variations and thermal shock, and other effects such as chemical reaction or radiation attack. They might also include other time-dependent primitive variables such as creep, mechanical fatigue, thermal aging, thermal fatigue, or even effects such as seasonal attack (see APPENDIX A, Primitive Variables, Symbols, and Units). For most of these primitive variables, strength has been observed to decrease with an increase in the variable.

The postulated constitutive equation accounts for the degradation of strength due to these primitive variables. The general form of the equation is

$$\frac{S}{S_0} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i} \quad (1)$$

where A_i , A_{iF} and A_{iO} are the current, ultimate and reference values of a particular effect, a_i is the value of an empirical constant for the i^{th} effect or primitive variable, n is the number of product terms of primitive variables in the model, and S and S_0 are the current and reference values of material strength. Each term has the property that if the current value equals the ultimate value, the current strength will be zero. Also, if the current value equals the reference value, the term equals one and strength is not affected by that variable.

This deterministic constitutive model may be calibrated by an appropriately curve-fitted least squares multiple linear regression of experimental data [7], perhaps supplemented by expert opinion. Ideally, experimental data giving the relationship between effects and strength is obtained. For example, data for just one effect could be plotted on log-log paper. A good fit for the data is then obtained by a linear regression analysis. This is illustrated schematically in Figure 1. The postulated constitutive equation, for a single

effect, is then obtained by noting the linear relation between $\log S$ and $\log \left[\frac{A_F - A_O}{A_F - A} \right]$,

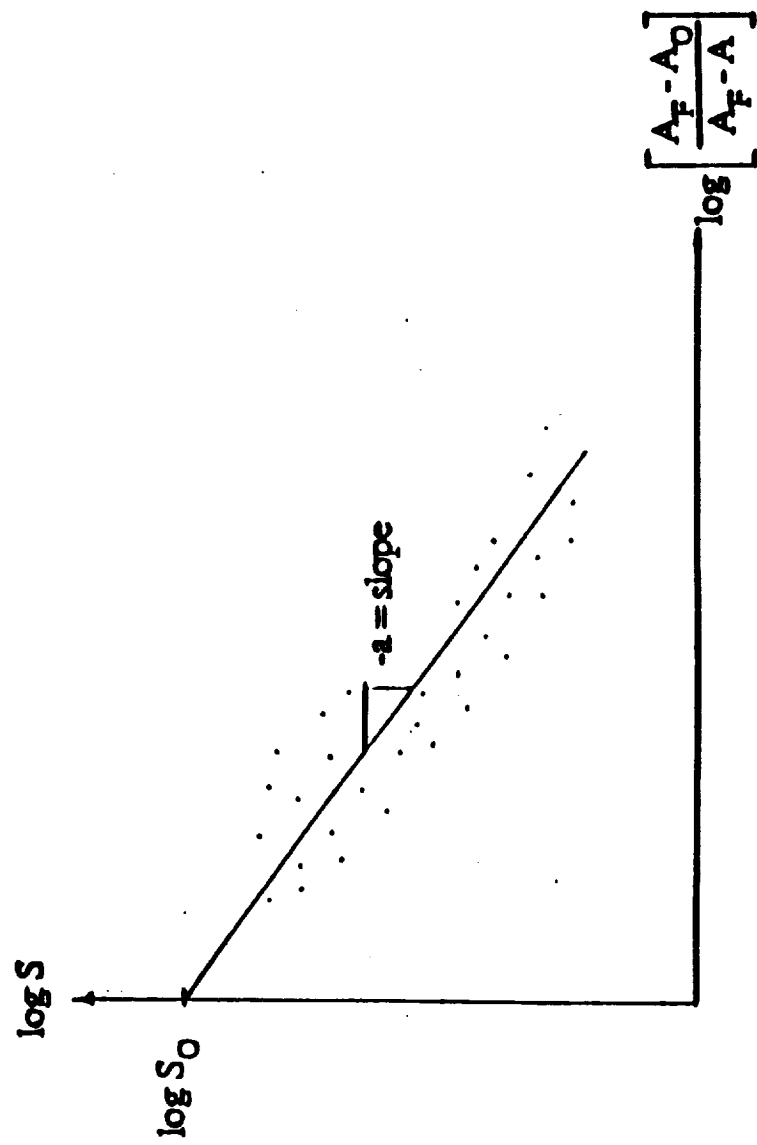


Fig. 1 Schematic of experimental data illustrating the effect of one primitive variable on strength.

as follows:

$$\begin{aligned}
 \log S &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] + \log S_O \\
 \log S - \log S_O &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \log \frac{S}{S_O} &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \frac{S}{S_O} &= \left[\frac{A_F - A_O}{A_F - A} \right]^{-a} \\
 \frac{S}{S_O} &= \left[\frac{A_F - A}{A_F - A_O} \right]^a
 \end{aligned} \tag{2}$$

Note that the above equation (2) is for a primitive variable that lowers strength. If a variable raises strength, the exponent is negative.

This general constitutive model may be used to estimate the strength of an aerospace propulsion system component under the influence of a number of diverse effects or primitive variables. The probabilistic treatment of this equation includes randomizing the deterministic multifactor interaction constitutive equation, performing probabilistic analysis by simulation and generating probability density function (p.d.f.) estimates for strength using a non-parametric method, maximum penalized likelihood [8,9]. Integration yields the cumulative distribution function (c.d.f.) from which probability statements regarding strength may be made. This probabilistic constitutive model predicts the random strength of an aerospace propulsion component due to a number of diverse random effects.

This probabilistic constitutive model is embodied in two FORTRAN programs, PROMISS (Probabilistic Material Strength Simulator) and PROMISC (Probabilistic Material Strength Calibrator); see Final Technical Report, APPENDIX 2. PROMISS calculates the random strength of an aerospace propulsion component due to as many as eighteen diverse random effects. Results are presented in the form of probability density functions and cumulative distribution functions of normalized strength, S/S_O . PROMISC calculates the values of the empirical material constants, a_i .

PROMISS includes a relatively simple "fixed" model as well as a "flexible" model. The fixed model postulates a probabilistic constitutive equation that considers the primitive variables given in Table 1. The general form of this constitutive equation is given in equation (1), wherein there are now $n = 7$ product terms, one for each effect or primitive variable listed above. Note that since this model has seven primitive variables, each containing four values of the variable, it has a total of twenty-eight variables. The flexible model postulates a probabilistic constitutive equation that considers up to as many as $n = 18$ product terms for primitive variables. These variables may be selected to utilize the theory and experimental data currently available for the specific strength degradation mechanisms of interest. The specific effects included in the flexible model are listed in Table 2. Note that in order to provide for future expansion and customization of the flexible model, six "other" effects have been provided.

Table 1 Primitive variables available in the fixed model

i^{th} Primitive Variable	Primitive Variable Type
1	Stress due to static load
2	Temperature
3	Chemical reaction
4	Stress due to impact
5	Mechanical fatigue
6	Thermal fatigue
7	Creep

Table 2 Primitive variables available in the flexible model

A. Environmental Effects

1. Mechanical
 - a. Stress
 - b. Impact
 - c. Other Mechanical Effect
2. Thermal
 - a. Temperature Variation
 - b. Thermal Shock
 - c. Other Thermal Effect
3. Other Environmental Effects
 - a. Chemical Reaction
 - b. Radiation Attack
 - c. Other Environmental Effect

B. Time-Dependent Effects

1. Mechanical
 - a. Creep
 - b. Mechanical Fatigue
 - c. Other Mech. Time-Dep. Effect
2. Thermal
 - a. Thermal Aging
 - b. Thermal Fatigue
 - c. Other Thermal Time-Dep. Effect
3. Other Time-Dependent Effects
 - a. Corrosion
 - b. Seasonal Attack
 - c. Other Time-Dep. Effect

The considerable scatter of experimental data and the lack of an exact description of the underlying physical processes for the combined mechanisms of fatigue, creep, temperature variations, and so on, make it natural, if not necessary to consider probabilistic models for a strength degradation model. Therefore, the fixed and flexible models corresponding to equation (1) are "randomized", and yield the "random normalized material strength due to a number of diverse random effects or primitive variables." Note that for the fixed model, equation (1) has the following form:

$$S/S_0 = f(A_{1F}, A_1, A_{1O}, A_{2F}, A_2, A_{2O}, \dots, A_{7F}, A_7, A_{7O}) \quad (3)$$

where A_i , A_{iF} and A_{iO} are the ultimate, current and reference values of the i^{th} of seven effects or primitive variables as given in Table 1. In general, this expression can be written as,

$$S/S_0 = f(X_i), i = 1, \dots, 28, \quad (4)$$

where the X_i are the twenty eight independent variables in equation (3). Thus, the fixed model is "randomized" by assuming all the independent variables, X_i , $i = 1, \dots, 28$, to be random and stochastically independent. For the flexible model, equation (1) has a form analogous to equations (3) and (4), except that there are as many as seventy-two independent variables. Applying probabilistic analysis to either of these randomized equations yields the distribution of the dependent random variable, normalized material strength, S/S_0 .

Although a number of methods of probabilistic analysis are available, [8] simulation was chosen for PROMISS. Simulation utilizes a theoretical sample generated by numerical techniques for each of the independent random variables. One value from each sample is substituted into the functional relationship, equation (3), and one realization of normalized strength, S/S_0 , is calculated. This calculation is repeated for each value in the set of samples, yielding a distribution of different values for normalized strength.

A probability distribution function is generated from these different values of normalized strength, using a non-parametric method, maximum penalized likelihood. Maximum penalized likelihood generates the p.d.f. estimate using the method of maximum likelihood together with a penalty function to smooth it [9]. Finally, integration of the generated p.d.f. results in the cumulative distribution function, from which probabilities of normalized strength can be directly observed.

PROMISS includes computational algorithms for both the fixed and the flexible probabilistic constitutive models. As described above, PROMISS randomizes the following equation:

$$\frac{S}{S_0} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i} \quad (5)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_i , A_{iF} and A_{iO} are random variables, a_i is the i^{th} empirical material constant and S/S_O is normalized strength. There are a maximum of eighteen possible effects or primitive variables that may be included in the model. For the flexible model option, they may be chosen by the user from those in Table 2. For the fixed model option, the primitive variables of Table 1 are chosen. Within each primitive variable term the current, ultimate and reference values and the empirical material constant may be modeled as either deterministic (empirical, calculated by PROMISC), normal, lognormal, or Wiebull random variables. Simulation is used to generate a set of realizations for normalized random strength, S/S_O , from a set of realizations for primitive variables and empirical material constants. Maximum penalized likelihood is used to generate an estimate for the p.d.f. of normalized strength, from a set of realizations of normalized strength. Integration of the p.d.f. yields the c.d.f. Plot files are produced to plot both the p.d.f. and the c.d.f. PROMISS also provides information on S/S_O statistics (mean, variance, standard deviation and coefficient of variation). A resident database, for database rather than user input of empirical material constants, is also provided.

PROMISC (see Final Technical Report, APPENDIX 2) performs a multiple linear regression on actual experimental or simulated experimental data for as many as eighteen effects or primitive variables, yielding regression coefficients that are the empirical material constants, a_i , required by PROMISS. It produces the multiple linear regression of the log transformation of equation (3), the PROMISS equation. When transformed it becomes

$$\log \frac{S}{S_O} = \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (6)$$

or

$$\log S = \log S_O + \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (7)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_i , A_{iF} and A_{iO} are primitive variable data and a_i is the i^{th} empirical material constant, or the i^{th} regression coefficient to be predicted by PROMISC. Also, $\log S_O$ is the log transformed reference value of strength, or the intercept regression coefficient to be predicted by PROMISC, and $\log S$ is the log transformed strength.

Experimental data for up to eighteen possible effects, as given in Table 2, may be included. The primitive variable data may be either actual experimental data or expert opinion, directly read from input, or simulated data where expert opinion is specified as the mean and standard deviation of a normal or lognormal distribution. The simulated data option for input data was used in the early stages of code development to verify correct performance. The input data, whether actual or simulated, is read in and assembled into a data matrix. From this data matrix, a corrected sums of squares and cross products matrix is computed. From this sums of squares and cross products matrix, and a least squares methodology, a multiple linear regression is performed to calculate estimates for the empirical material constant, a_i , and the reference strength, S_0 . These are the regression coefficients.

PROMISC includes enhancements of the multiple linear regression analysis to screen data from "outliers" and collinearities, determine "how well" the data fit the regression, quantify the importance and relative importance of each factor in the postulated constitutive equation, eq. (1), as well as check assumptions inherent in the use of multiple linear regression. Further details are provided in the Final Technical Report, Section 6.0, NASA Grant No. NAG 3-867, Supp. 2, "Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation."

3.0 CASES FOR ANALYSIS BY PROMISS

This section presents cases for analysis that show the effect on probabilistic lifetime strength for each of several effects or primitive variables (quasi-static stress, mechanical fatigue, thermal fatigue and creep) at both high and low temperature conditions. The resulting sensitivity study utilized the PROMISS code "fixed" capability. A base line room temperature problem was established utilizing values derived from expert opinion and material properties typical of a cast nickel-base superalloy. The input for this problem is given in Table 3 and is similar to that used for the PROMISS example problem reported earlier [10]. For this room temperature problem, quasi-static stress was varied about 5% above and below the 90 ksi base line value. The results of PROMISS in the form of a c.d.f. is given in Figure 2. Then the base line value of 90 ksi for quasi-static stress was re-established, while mechanical fatigue, thermal fatigue and creep were each varied 5%, 5% and 90%, respectively about their base line values. The PROMISS output, again in the form of c.d.f. plots, for these results together with Figure 2 is given in Section 12.0, APPENDIX 3 as Figures A.1 to A.4. A second base line problem was established that was identical to the first, except that temperature was set to about 57% of T_m . For this high temperature problem, quasi-static stress was again varied about 5% above and below the 90 ksi base line value. The results of this PROMISS case are given in Figure 3. Then the base line value of 90 ksi for quasi-static stress was reestablished, while mechanical fatigue, thermal fatigue and creep were each varied 5%, 5% and 90%, respectively about their base line values. The PROMISS output for these results together with Figure 3 is also given in Section 12.0, APPENDIX 3 as Figures A.5 to A.8.

Conclusions drawn from this sensitivity study are summarized below. Raising temperature from room temperature to 57% T_m significantly decreases lifetime strength regardless of the primitive variable perturbed. Also, raising strength temperature somewhat decreases the *spread* of the three c.d.f. curves regardless of the primitive variable perturbed. Qualitative observations such as these are appropriate from current PROMISS example problems, however experimental data from actual interaction experiments must be used to obtain values for the empirical material constants before specific quantitative conclusions can be drawn for particular aerospace materials.

Table 3 PROMISS "fixed" model base line room temperature problem.

Effect or Primitive Variable	Variable Symbol	Units	Distribution Type	Mean	Standard Deviation (Value) (% of Mean)	
Quasi- Static Stress	SSF	ksi	Lognormal	130.0	6.5	5.0
	σ_S	ksi	Lognormal	90.0	4.5	5.0
	σ_{SO}	ksi	Lognormal	-2.9	-0.145	5.0
	p	N/A	Normal	0.5	0.015	3.0
Temperature	T _F	oF	Normal	2732.0	82.0	3.0
	T	oF	Normal	68.0	2.04	3.0
	T _O	oF	Normal	68.0	2.0	3.0
	q	N/A	Normal	0.5	0.015	3.0
Chemical Reaction	R _F	N/A	Normal	1.0	0.003	0.3
	R	N/A	Normal	0.02	0.0006	3.0
	R _O	N/A	Normal	0.001	0.00003	3.0
	r	N/A	Normal	0.5	0.015	3.0
Impact	S _D F	N/A	Normal	1.0	0.003	0.3
	σ_D	N/A	Normal	0.1	0.003	3.0
	σ_{DO}	N/A	Normal	0.001	0.00003	3.0
	s	N/A	Normal	-0.5	-0.015	3.0
Mechanical Fatigue	N _M F	log of cycle	Lognormal	7.0	0.7	10.0
	N _M	log of cycle	Lognormal	3.5	0.35	10.0
	N _{MO}	log of cycle	Lognormal	1.0	0.1	10.0
	t	N/A	Normal	0.5	0.015	3.0
Thermal Fatigue	N _T F	log of cycle	Lognormal	3.0	0.3	10.0
	N _T	log of cycle	Lognormal	2.3	0.23	10.0
	N _{TO}	log of cycle	Lognormal	1.0	0.1	10.0
	u	N/A	Normal	0.5	0.015	3.0
Creep	t _{CF}	hours	Lognormal	10,000.0	500.0	5.0
	t _C	hours	Lognormal	100.0	3.0	3.0
	t _{CO}	hours	Lognormal	0.083	0.0025	3.0
	v	N/A	Normal	0.5	0.015	3.0

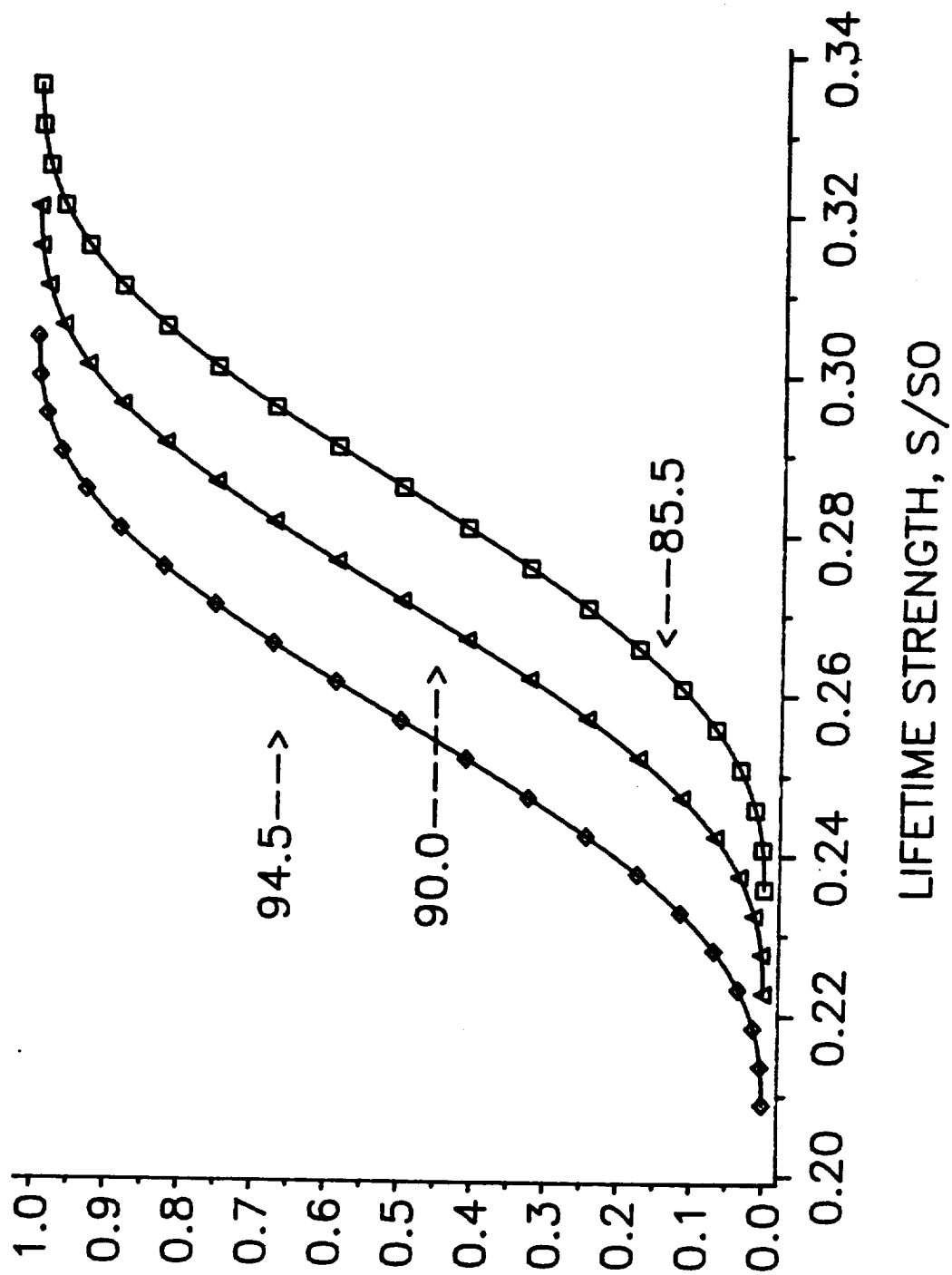


Figure 2 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF STRESS ON (ksi) PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT ROOM TEMPERATURE

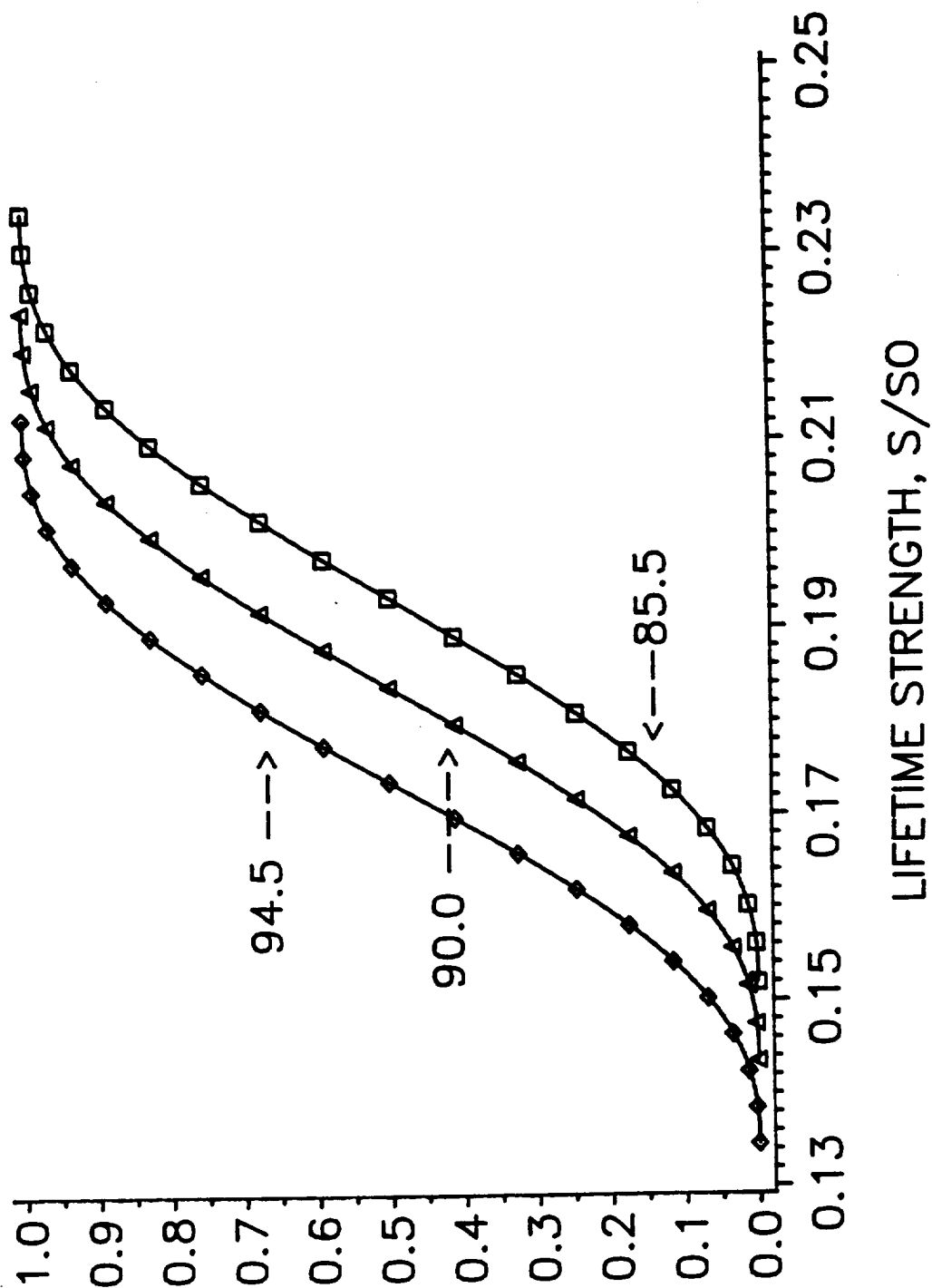


Figure 3 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF STRESS (ksi) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT 0.57 Tm

4.0 PROMISS AND PROMISC DOCUMENTATION

Complete documentation for both PROMISS AND PROMISC has been written, including both theory and user's instructions. This documentation has been appended to this Final Technical Report as APPENDIX 1 PROMISS USER MANUAL and APPENDIX 2 PROMISC USER MANUAL. These user manuals have also been issued under separate cover.

The manuals provide detailed instructions for input, description of output, and worked example problems. Example problems are given for both "fixed" and "flexible" models. The theory portion of the manuals contains a description of the probabilistic phenomenological constitutive relations for lifetime strength of materials, [11, 12], the randomized multifactor interaction constitutive equation, relevant probabilistic and statistical theory, a description of all effects or primitive variables available in the code, and a discussion of all algorithms. Manual appendices give tables listing effect or primitive variable names together with their symbols, FORTRAN names and units. Other appendices list sample problem input and output files and IMSL subroutines used by the codes. The PROMISS manual also gives a sample SAS/GRAPH program for plotting results. Both manuals also include *program notes* giving information helpful to the user in understanding the program.

5.0 INCREASED CAPABILITY OF PROMISS

The capability of the initial version of PROMISS was increased beyond the initial version developed at NASA Lewis during Summer, 1988. This new version is known as PROMISS, Ver. 2.0 and is fully documented in APPENDIX 1 of this report and under separate cover. PROMISS, Ver. 2.0 now includes calculation of the mean, variance, standard deviation and coefficient of variation of normalized strength (or lifetime strength) and incorporation of the Weibull as a statistical distribution to describe the uncertainty of any or all effects or primitive variables. Also a Resident Database was included in PROMISS for the empirical material constants, a_i . Thus, rather than the user selecting values for these material constants, he/she may elect to have the Resident Database supply a value. Currently all empirical material constants in the Resident Database are set to 0.5, a value set by expert opinion. As further materials data become available for specific aerospace materials, updated values will be incorporated into the Database.

6.0 INCREASED CAPABILITY OF PROMISC

The capability of the initial version of PROMISC was increased beyond the initial version developed at NASA Lewis during Summer, 1988. This new version is known as PROMISC, Ver. 2.0 and is fully documented in Section 10.0, APPENDIX 2 of this report and under separate cover. PROMISC, Ver. 2.0 now includes enhancements of the multiple linear regression analysis to determine "how well" the data fit the regression, to quantify the importance and relative importance of each effect or primitive variable in the postulated multifactor interaction equation, to screen data for "outliers" and collinearities, as well as to check assumptions inherent in the use of multiple linear regression.

Multiple linear regression is a least squares technique for fitting data to a linear equation. It can be carried out mathematically whether it is appropriate or not. Therefore, it can be used to test the validity of the model inherent in the multifactor interaction equation, by calculating "how well" the data fit the multiple linear regression through an Analysis of Variance (ANOVA) Table.

Through the use of the IMSL [1] subroutine RSTAT, procedures were included in PROMISC that, not only assess the validity of the model inherent in the multifactor interaction equation, but also produce diagnostics to check for violations of the assumptions inherent in the use of multiple linear regression. Subroutine RSTAT supplies an Analysis of Variance (ANOVA) Table, which quantifies the amount of variation in the data that can be explained by the multiple linear regression equation. This table is therefore an effective method for testing the model validity inherent in the multifactor interaction equation. Subroutine RSTAT also supplies a Sequential Statistics Table, which quantifies the importance of each factor in the multifactor interaction equation. RSTAT can be enhanced with the capability to do a stepwise regression on the multifactor interaction equation. The relative importance of each term is assessed through a p-value which appears in the Table under the Column headed by "Prob. of Larger F". The closer that each p-value is to zero then the more predictive capability that associated factor has.

Likewise, data may need to be screened for aberrant observations known as "outliers", through the IMSL routine RCASE. One of the most effective methods for outlier detection is Cook's Distance which is given in the subroutine as Cook's D. The problems associated with collinearities in the data can be explained through principal components regression.

The subroutine RSTAT provides an Inference on Coefficient Table, which embellishes the results of the Sequential Statistics Table with a column headed by "Variance Inflation Factor". This is a diagnostic procedure for checking for the violation of assumptions used in multiple linear regression. The Case Analysis Table (from the IMSL subroutine RCASE) is useful in detecting outliers (Cook's D) and collinearities in the data. The residuals and studentized residuals can be used to test the assumption of normality. In this way, one can test the validity of all the assumptions in the multiple linear regression equation. A thorough discussion of two examples is given in APPENDIX 2, PROMISC User Manual, Section 3.0.

7.0 MATERIALS DATA FOR RESIDENT DATABASE

7.1 Introduction

In order to anchor the empirical material constants, a_i , in the multifactor interaction equation to particular aerospace materials of interest, it is necessary to collect experimental data. No actual experiments were planned for this project, but instead data were collected from the open literature. All data obtained from the literature for this project were plotted and displayed in Section 13.0, Appendix 4. Data for nickel-base superalloys were far more abundant than that for metal matrix materials. Data for INCONEL 718 were also more abundant than for any other superalloy and were available for three primitive effects, namely high-temperature tensile*, mechanical fatigue and creep. Thus, certain INCONEL 718 data was selected and plotted in other forms, one of which was the same as that used by the multifactor interaction equation in PROMISS and PROMISC (see Section.7.4).

7.2 Literature Search

A computerized literature search of nickel-base superalloys and metal matrix composites was conducted to obtain existing experimental data on various material properties. Useful data on high-temperature tensile, mechanical fatigue and creep properties were found in eight of the sources (see Section 7.5 containing the material bibliography page).

7.3 Materials Data Discussion

Data on high-temperature tensile, mechanical fatigue and creep properties were obtained for nickel-base superalloys, however, only creep properties were found for metal matrix composites. Although there is evidence to indicate that fatigue and creep processes interact to produce a synergistic response [1], no data on combined effects were found. In addition, several sources provided substantial data on INCONEL 718, a nickel-base superalloy. Therefore, this superalloy will be discussed separately from the other nickel-base superalloys. All acquired data were entered into computer input files from which plots could be made. Plot files were created using SAS/GRAPH software [2]. Plots from both nickel-base superalloy and metal matrix composite data are provided in Section 13.0, Appendix 4.

7.3.1 INCONEL 718

As stated above, high-temperature tensile, mechanical fatigue and creep data were obtained for the nickel-base superalloy, INCONEL 718. The data resulted from tests done on various hot and cold worked specimens of INCONEL 718. Tests were conducted on sheets of INCONEL 718 and hot rolled bars of the superalloy. Some high-temperature tensile and creep property data resulted from tests performed on notched specimens with a stress concentration factor, K_t , ranging from 2.3 to greater than 20. Plots of tensile, fatigue and creep data for INCONEL 718 are given in Section 13.2, Appendix 4.

* also referenced as "Temperature" in other parts of this Final Technical Report and in the User Manuals.

7.3.2 Other Nickel-Base Superalloys

High-temperature tensile data were found for the thirteen nickel-base superalloys given in Table 4.

Table 4 Nickel-Base Superalloys

NUMBER	NICKEL-BASE SUPERALLOY
1	ASTROLOY
2	HASTELLOY X
3	IN-102
4	IN-939
5	INCONEL 600
6	INCONEL 601
7	INCONEL X-750
8	MAR-M421
9	MM-006
10	NIMONIC 80A
11	NIMONIC 115
12	PWA 1480 SC
13	RENE 41

Data on fatigue properties were found for only one superalloy, INCONEL 601. As with the INCONEL 718 specimens, test specimens of the other nickel-base superalloys were subjected to prior hot and cold work as noted on the plots. These plots are provided in Section 13.3, Appendix 4.

7.3.3 Metal Matrix Composites

Metal matrix composite data were far more scarce than nickel-base superalloy data. Only test data on creep properties were found. Data on high-temperature tensile or fatigue properties could not be found for any metal matrix composite. Data on creep behavior were obtained for Tungsten/Niobium and Tungsten/Niobium-1 Percent Zirconium composites. Two types of Tungsten fibers, 218CS and ST300, were tested as reinforcement material. Creep behavior plots of the metal matrix composites, as well as the Tungsten fibers, are provided in Section 13.4, Appendix 4.

7.4 Data Selected for Presentation in PROMISS and PROMISC Form

7.4.1 High-Temperature Tensile Data

Plots of high-temperature tensile, mechanical fatigue and creep data for the nickel-base superalloy, INCONEL 718, are provided in this section. Figure 4 shows the effect of temperature on the yield strength of the material. As expected, the yield strength of the material decreases as the temperature increases.

Figure 5 is a plot of the data from Figure 4 that has been normalized with respect to melting temperature and yield strength at room temperature. The data along the x-axis were normalized by dividing each temperature value by the melting temperature, T_m , of the superalloy. The data along the y-axis were normalized by dividing the yield strength values by the material's yield strength at room temperature. Note in Figure 5, that the strength begins to drastically decrease at a temperature that is about 50% of the melting temperature.

Figure 6 is a plot of the log of the same data (Fig. 4) with only the x-axis normalized. The data along the x-axis were normalized with respect to both melting temperature, T_m , and a reference temperature (taken as room temperature), T_o . In order to calculate the normalized values, the difference between the melting temperature, T_m , and a reference temperature, T_o , was computed. This value was then divided by the difference between the melting temperature and each temperature value, T , from Fig. 4. Finally, the log of each normalized value was plotted along the x-axis. Thus, the x-axis values were calculated from

$$x = \log \left[\frac{(T_m - T_o)}{(T_m - T)} \right].$$

For example, the x-location of the second data point was calculated using

$$x = \log \left[\frac{(2369 - 75)}{(2369 - 600)} \right] = .113 ,$$

where 2369° F is the melting temperature and 600° F is the x-axis value of the 2nd data point in Fig. 4. The y-axis values were calculated by taking the log of each yield strength value from Fig. 4. Referring once again to the second data point, the y-location was calculated using $y = \log 156 = 2.193$, where 156 ksi is the y-axis value of the 2nd data point in Fig. 4.

HOT-ROLLED ROUND
ANNEALED AT 1950 °F

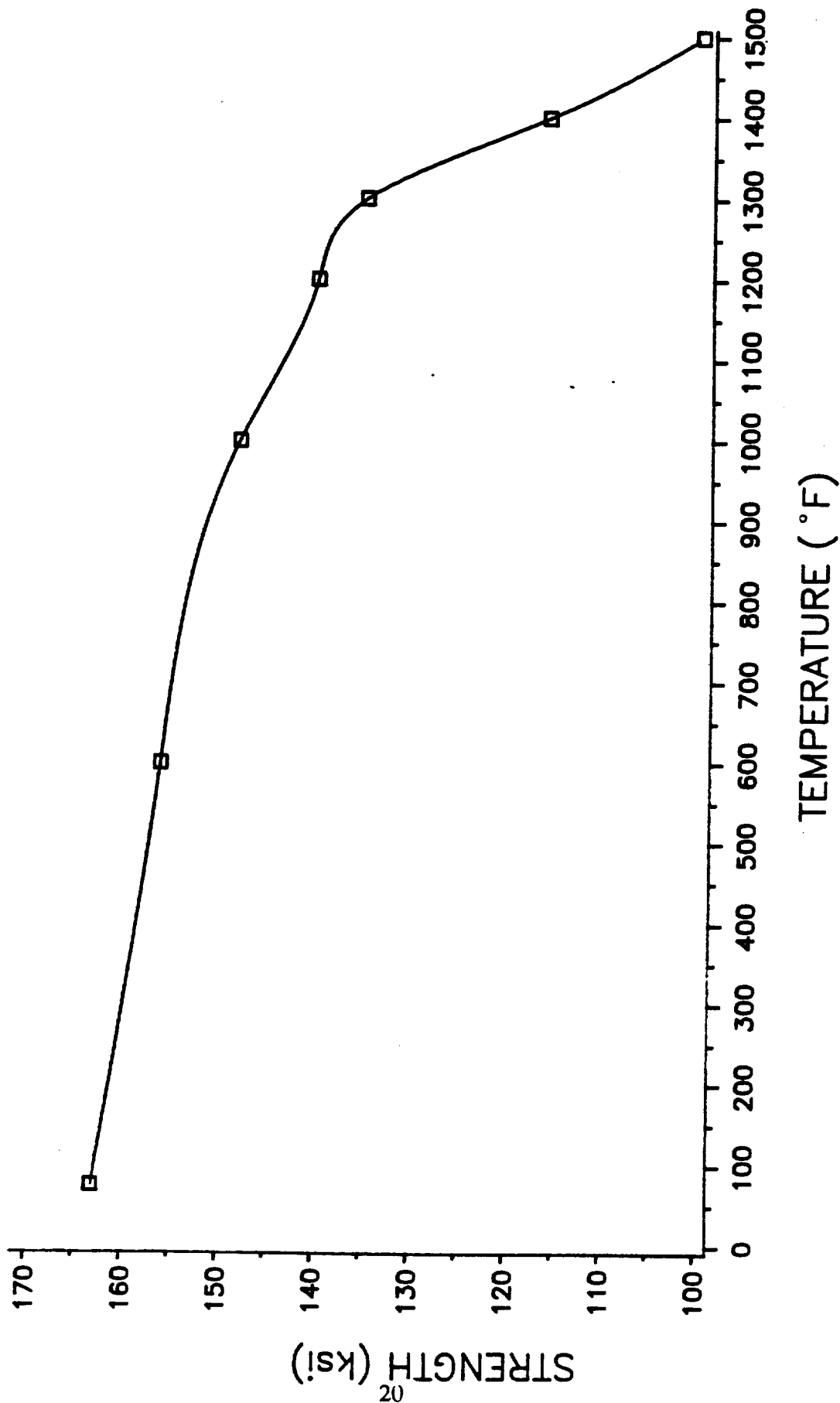


Figure 4 Effect of Temperature on Yield Strength
for INCONEL 718, Raw Data

HOT-ROLLED ROUND
 ANNEALED AT 1950 F
 R.T.=75 F, T_m=2369 F

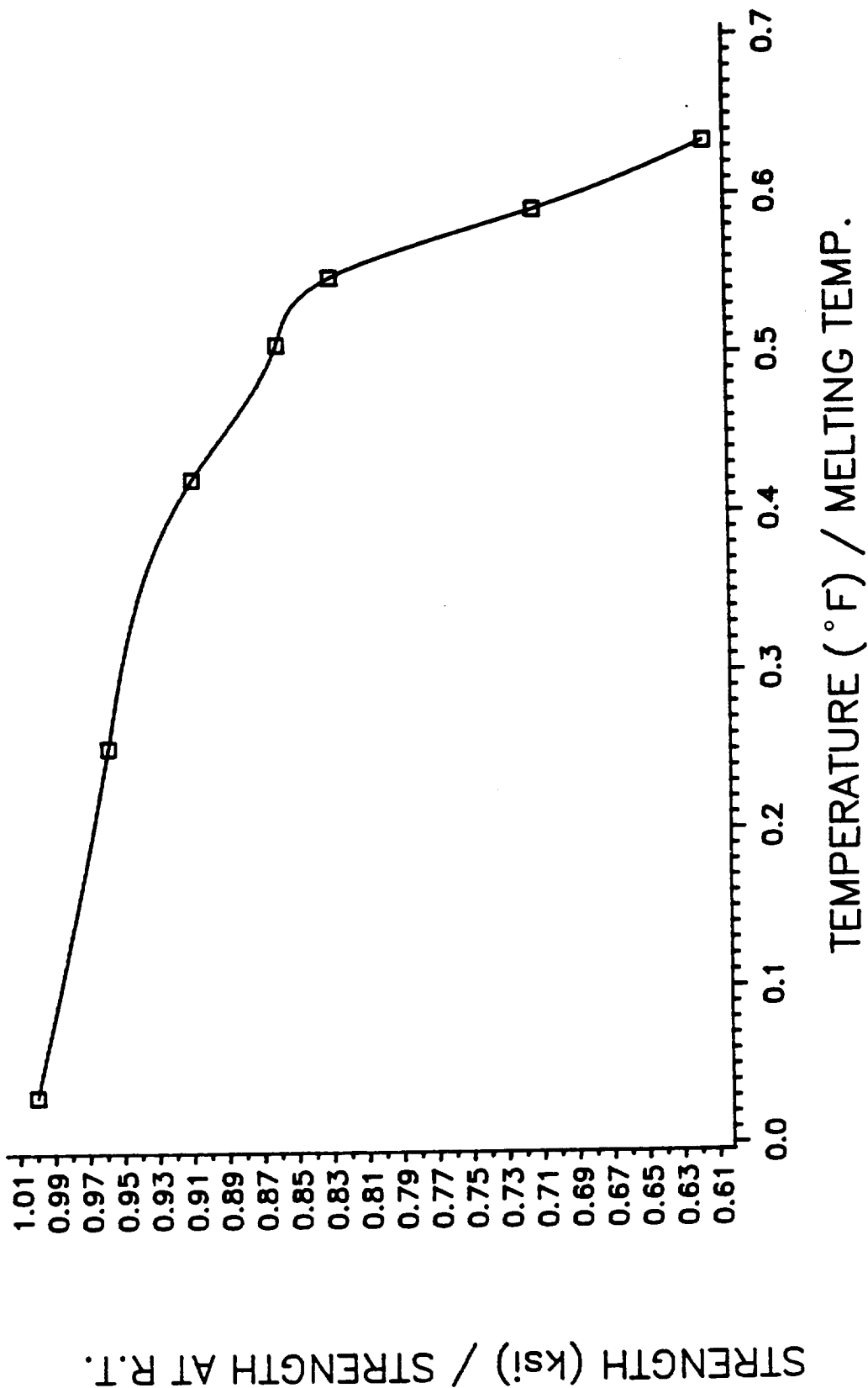


Figure 5 Effect of Temperature on Yield Strength
 for INCONEL 718, Normalized Data

HOT-ROLLED ROUND
ANNEALED AT 1950 F
 $T_o=75$ F, $T_m=2369$ F

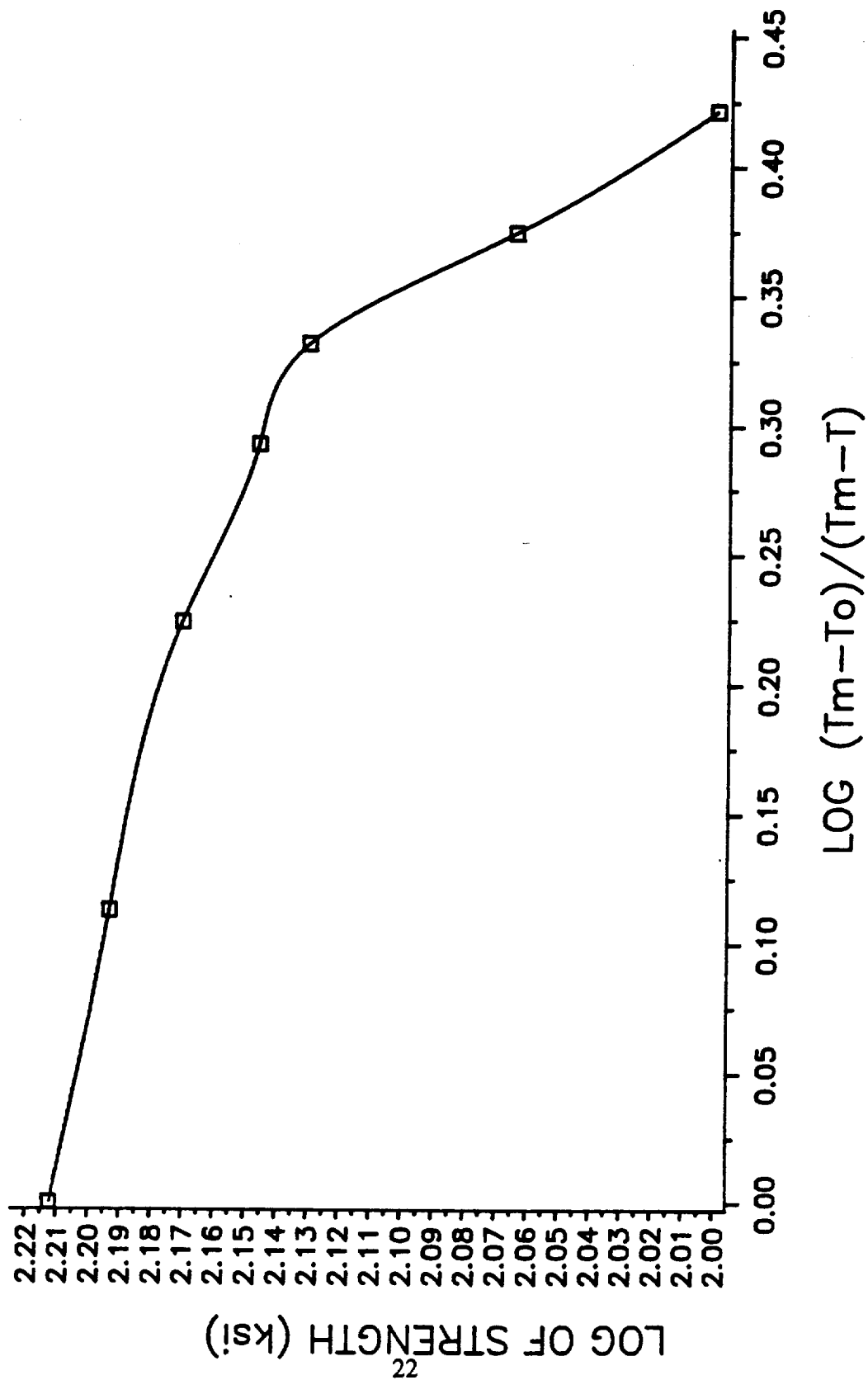


Figure 6 Effect of Temperature on Yield Strength
for INCONEL 718, Log of Renormalized Data

7.4.2 Mechanical Fatigue Data

Figure 7 shows the effect of cycles on fatigue strength for INCONEL 718 given a set testing temperature. As seen from the figure, the fatigue strength of the material decreases as the number of cycles increases.

Figure 8 is a plot of the data from Figure 7 that has been normalized along both axes. The data along the x-axis were normalized by dividing the fatigue cycle values by the material's fatigue cycle value at minimum fatigue strength. Thus, the x-axis values were calculated from

$$x = \left[\frac{\text{Fatigue Cycles}}{\text{Fatigue Cycles at Minimum Strength}} \right]$$

For example, the x-location of the third data point was calculated using

$$x = \left[\frac{10000 \times 10^3}{100000 \times 10^3} \right] = 0.1 ,$$

where (10000×10^3) and (100000×10^3) cycles are the x-axis values of the 3rd and 4th data points, respectively, in Fig. 7. Note that the x-axis value of the 4th data point in Fig. 7 is the above-mentioned material's fatigue cycle value at minimum fatigue strength. The data along the y-axis were normalized by dividing the material's fatigue strength values by its fatigue strength value at 0.1% of the fatigue cycle value at minimum fatigue strength. For example, the y-location of the third data point was calculated using

$$y = \left[\frac{95}{111} \right] = .856 ,$$

where 111 and 95 ksi are the y-axis values of the 1st and 3rd data points, respectively, in Fig. 7. The 111 ksi value (y-axis value of the 1st data point in Fig. 7) is the material's fatigue strength at 0.1% of the fatigue cycles at minimum strength, or in other words, 111 ksi is the material's fatigue strength at $0.1\% \times (100000 \times 10^3)$ or (100×10^3) cycles.

Figure 9 is a plot of the log of the same data (Fig. 7) with only the x-axis normalized. The data along the x-axis were normalized with respect to FC_{\max} and FC_{\min} , where FC_{\max} is the material's fatigue cycle value at minimum fatigue strength and FC_{\min} is 0.1% of the fatigue cycle value at minimum fatigue strength. In order to calculate the normalized values, the difference between FC_{\max} and FC_{\min} was computed. This value was then divided by the difference between FC_{\max} and each fatigue cycle value, FC , from Fig. 7. Finally, the log of each normalized value was plotted along the x-axis. Thus, the x-axis values were calculated from

$$x = \log \left[\frac{(FC_{\max} - FC_{\min})}{(FC_{\max} - FC)} \right]$$

For example, the x-location of the third data point was calculated using

$$x = \log \left[\frac{(100000 \times 10^3 - 100 \times 10^3)}{(100000 \times 10^3 - 10000 \times 10^3)} \right] = .0453 ,$$

where (100×10^3) , (10000×10^3) and (100000×10^3) are the x-axis values of the 1st, 3rd and 4th data points, respectively, in Fig. 7. The y-axis values were calculated by taking

the log of each fatigue strength value. Referring once again to the third data point, the y-location was calculated using $y = \log 95 = 1.978$, where 95 ksi is the y-axis value of the 3rd data point in Fig. 7.2.1.

TEST TEMP. = 1000 F

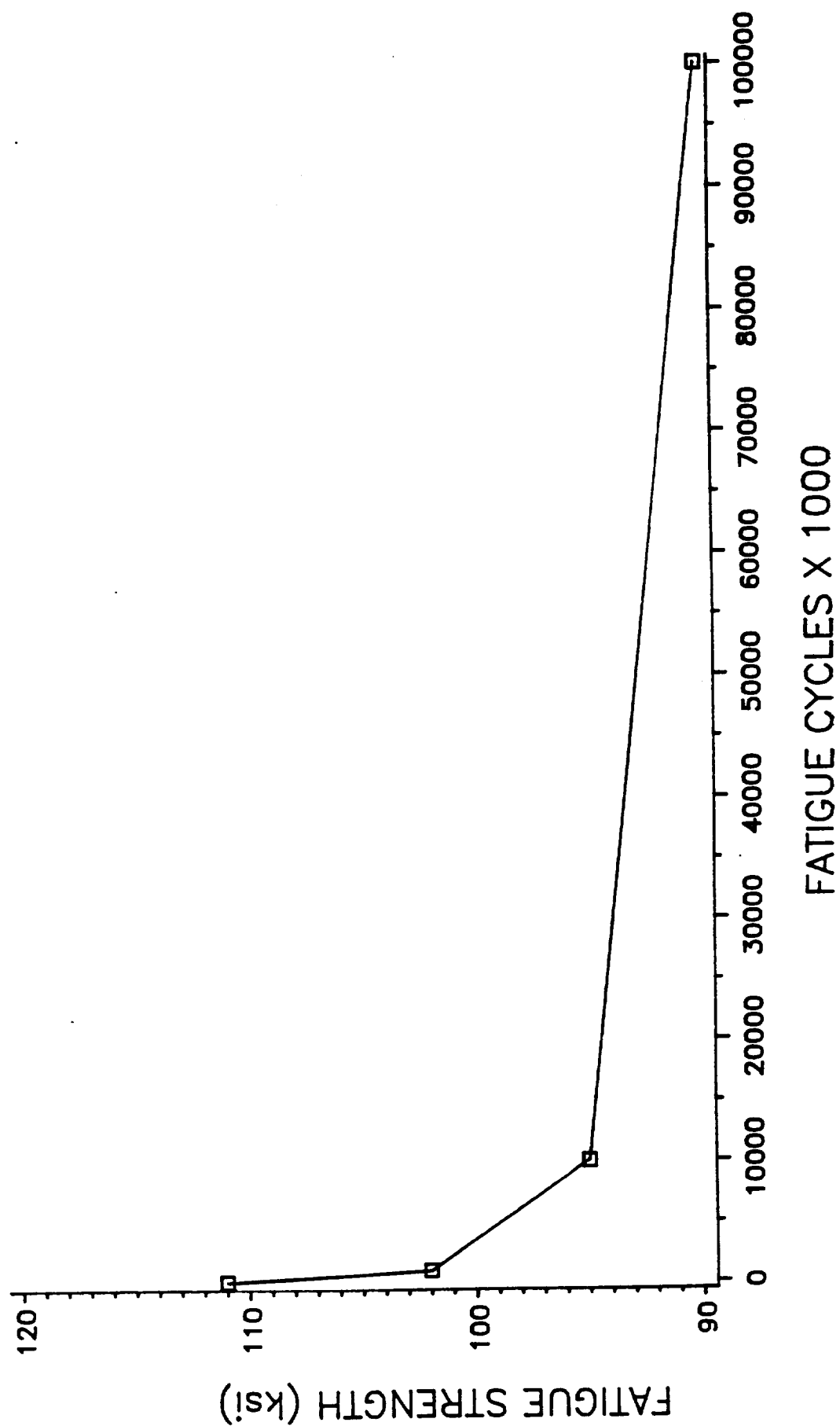


Figure 7 Effect of Cycles on Fatigue Strength
for INCONEL 718, Raw Data

TEST TEMP. = 1000 F

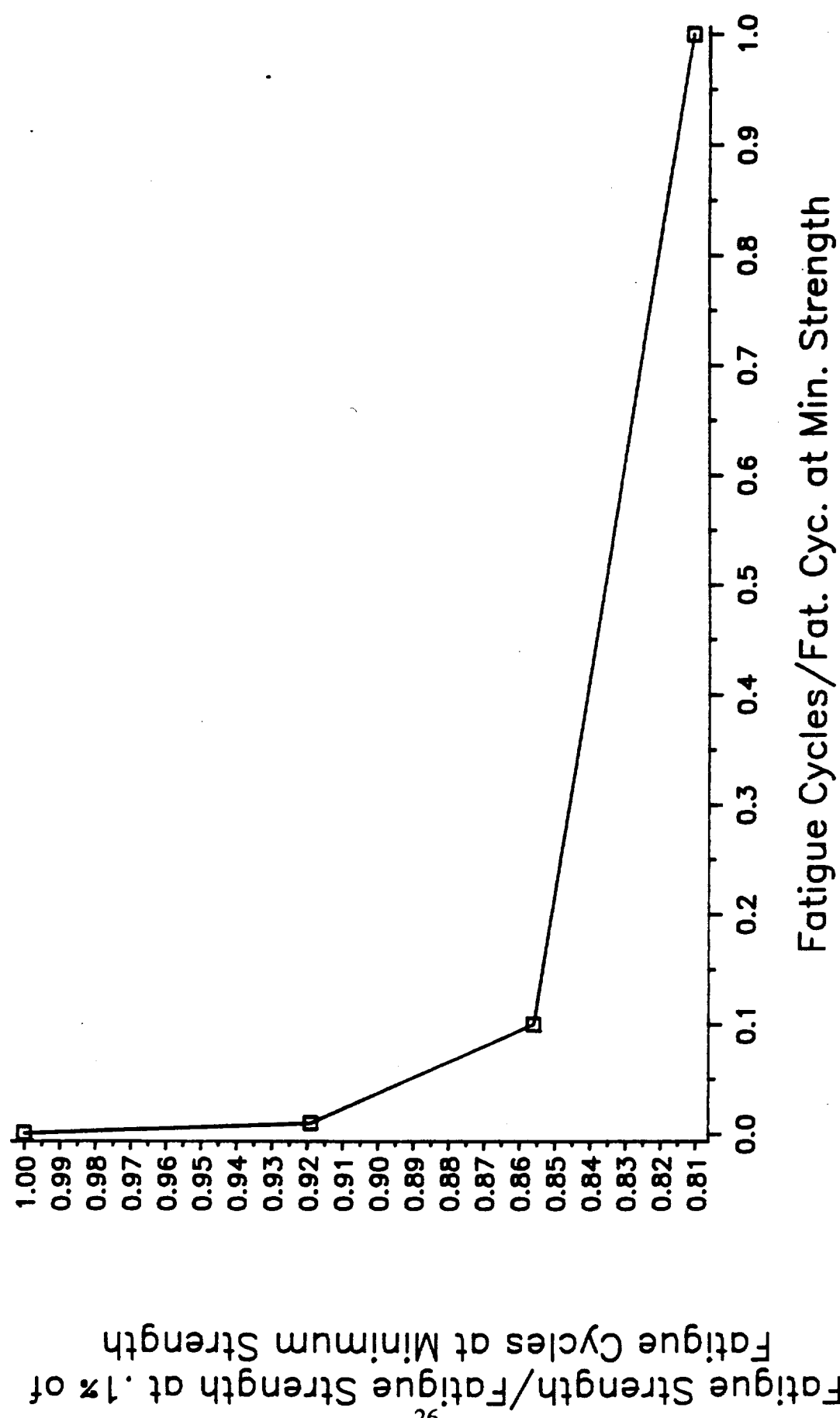


Figure 8 Effect of Cycles on Fatigue Strength for INCONEL 718, Normalized Data

TEST TEMP. = 1000° F

FC_{max} = Fatigue Cycles at Minimum

Fatigue Strength

FC_{min} = 0.1% of Fatigue Cycles at Minimum

Fatigue Strength

FC = Given Fatigue Cycle Value

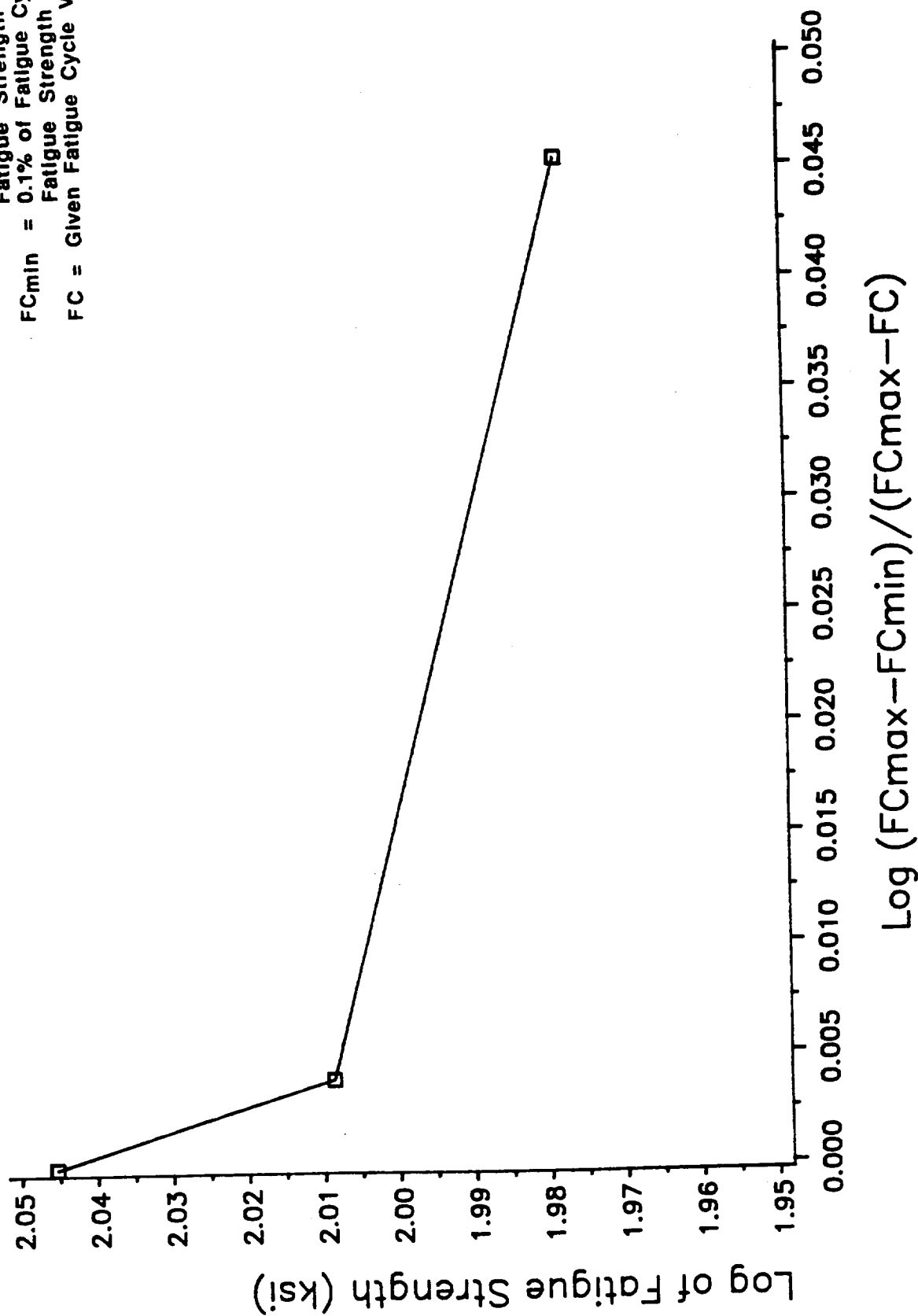


Figure 9 Effect of Cycles on Fatigue Strength for INCONEL 718, Log of Renormalized Data

7.4.3 Creep Data

Figure 10 shows the effect of time on rupture strength for INCONEL 718 given a set testing temperature. As seen from the figure, the rupture strength of the material decreases as the rupture life increases.

Figure 11 is a plot of the data from Figure 10 that has been normalized along both axes. The data along the x-axis were normalized by dividing the rupture life values by the material's rupture life value at minimum rupture strength. Thus, the x-axis values were calculated from

$$x = \left[\frac{\text{Rupture Life}}{\text{Rupture Life at Minimum Strength}} \right].$$

For example, the x-location of the sixth data point was calculated using

$$x = \left[\frac{8473.0}{21523.6} \right] = 0.394 ,$$

where 8473.0 and 21523.6 hours are the x-axis values of the 6th and 7th data points, respectively, in Fig. 10. Note that the x-axis value of the 7th data point in Fig. 7 is the above-mentioned material's rupture life value at minimum rupture strength. The data along the y-axis were normalized by dividing the material's rupture strength values by its rupture strength value at 0.13% of the rupture life at minimum rupture strength. For example, the y-location of the sixth data point was calculated using

$$y = \left[\frac{124}{158} \right] = .785 ,$$

where 158 and 124 ksi are the y-axis values of the 1st and 6th data points, respectively, in Fig. 10. The 158 ksi value (y-axis value of the 1st data point in Fig. 10) is the material's rupture strength at 0.13% of the rupture life at minimum strength, or in other words, 158 ksi is the material's rupture strength at $(0.13\% \times 21523.6)$ or 27.8 hours.

Figure 12 is a plot of the log of the same data (Fig. 10) with only the x-axis normalized. The data along the x-axis were normalized with respect to RL_{\max} and RL_{\min} , where RL_{\max} is the material's rupture life value at minimum rupture strength and RL_{\min} is 0.13% of the rupture life value at minimum rupture strength. In order to calculate the normalized values, the difference between RL_{\max} and RL_{\min} was computed. This value was then divided by the difference between RL_{\max} and each rupture life value, RL , from Fig. 10. Finally, the log of each normalized value was plotted along the x-axis. Thus, the x-axis values were calculated from

$$x = \log \left[\frac{(RL_{\max} - RL_{\min})}{(RL_{\max} - RL)} \right].$$

For example, the x-location of the sixth data point was calculated using

$$x = \log \left[\frac{(21523.6 - 27.8)}{(21523.6 - 8473.0)} \right] = .217 ,$$

where 27.8, 8473.0 and 21523.6 are the x-axis values of the 1st, 6th and 7th data points, respectively, in Fig. 10. The y-axis values were calculated by taking the log of each

rupture strength value. Referring once again to the sixth data point, the y-location was calculated using $y = \log 124 = 2.093$, where 124 ksi is the y-axis value of the 6th data point in Fig. 10 .

TEST TEMP. = 1000 F

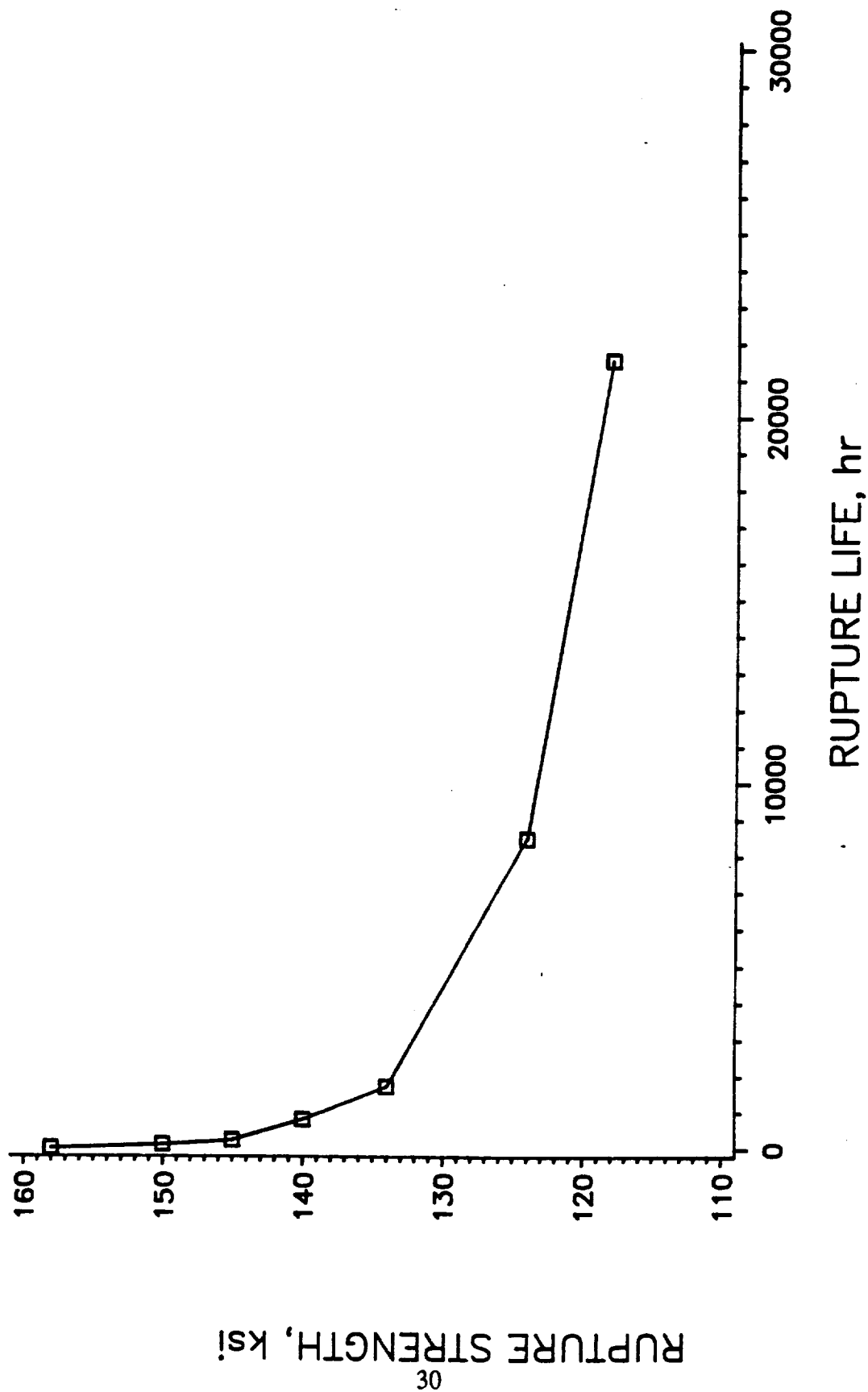


Figure 10 Effect of Time on Rupture Strength
for INCONEL 718, Raw Data

TEST TEMP. = 1000 F

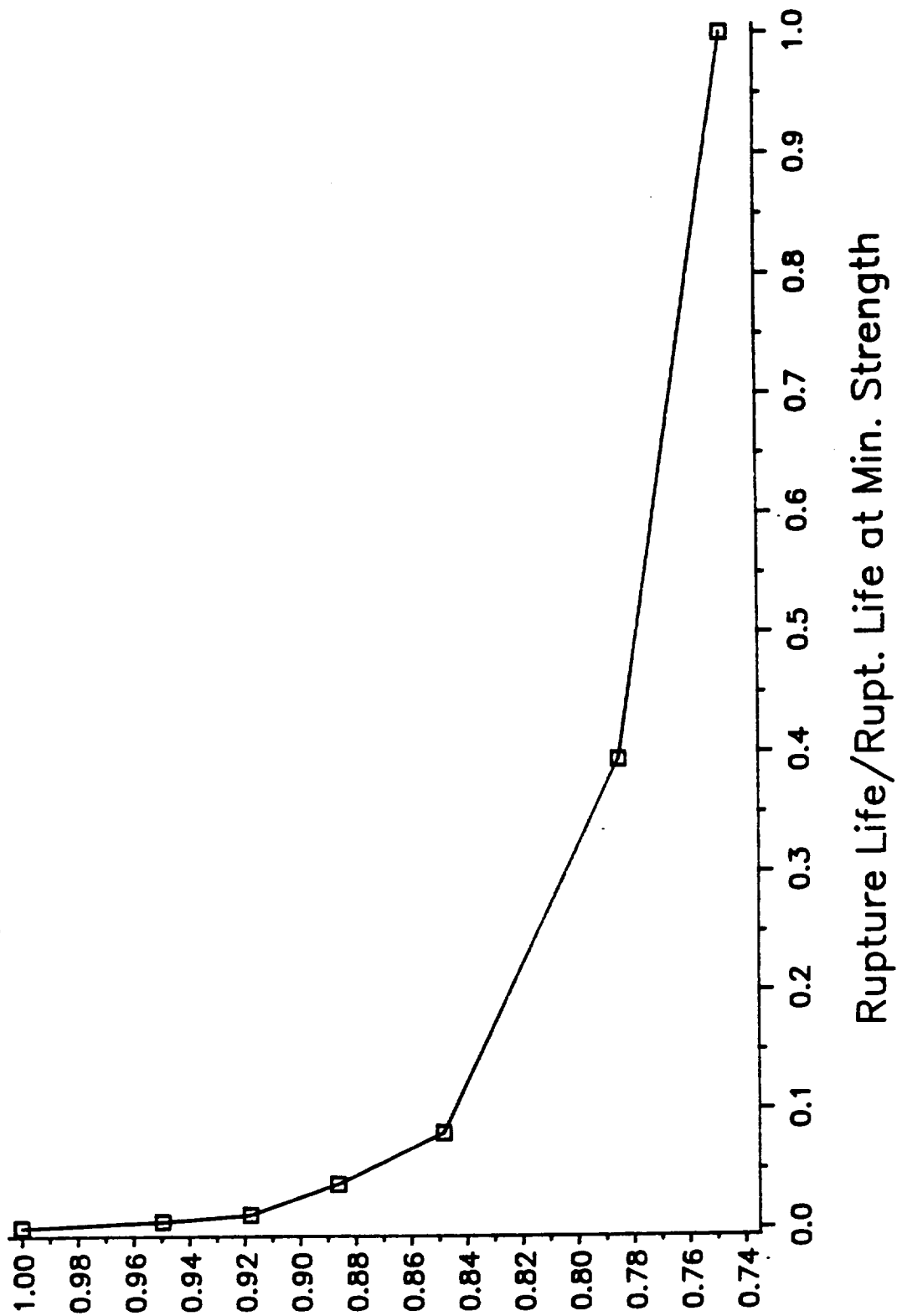


Figure 11 Effect of Time on Rupture Strength
for INCONEL 718, Normalized Data

Rupture Strength/Rupt. Life at Minimum Strength
The Rupture Life at Minimum Strength

TEST TEMP. = 1000° F

RLmax = Rupture Life at Minimum Strength

RLmin = 0.13% of Rupture Life at Minimum Strength

RL = Given Rupture Life Value

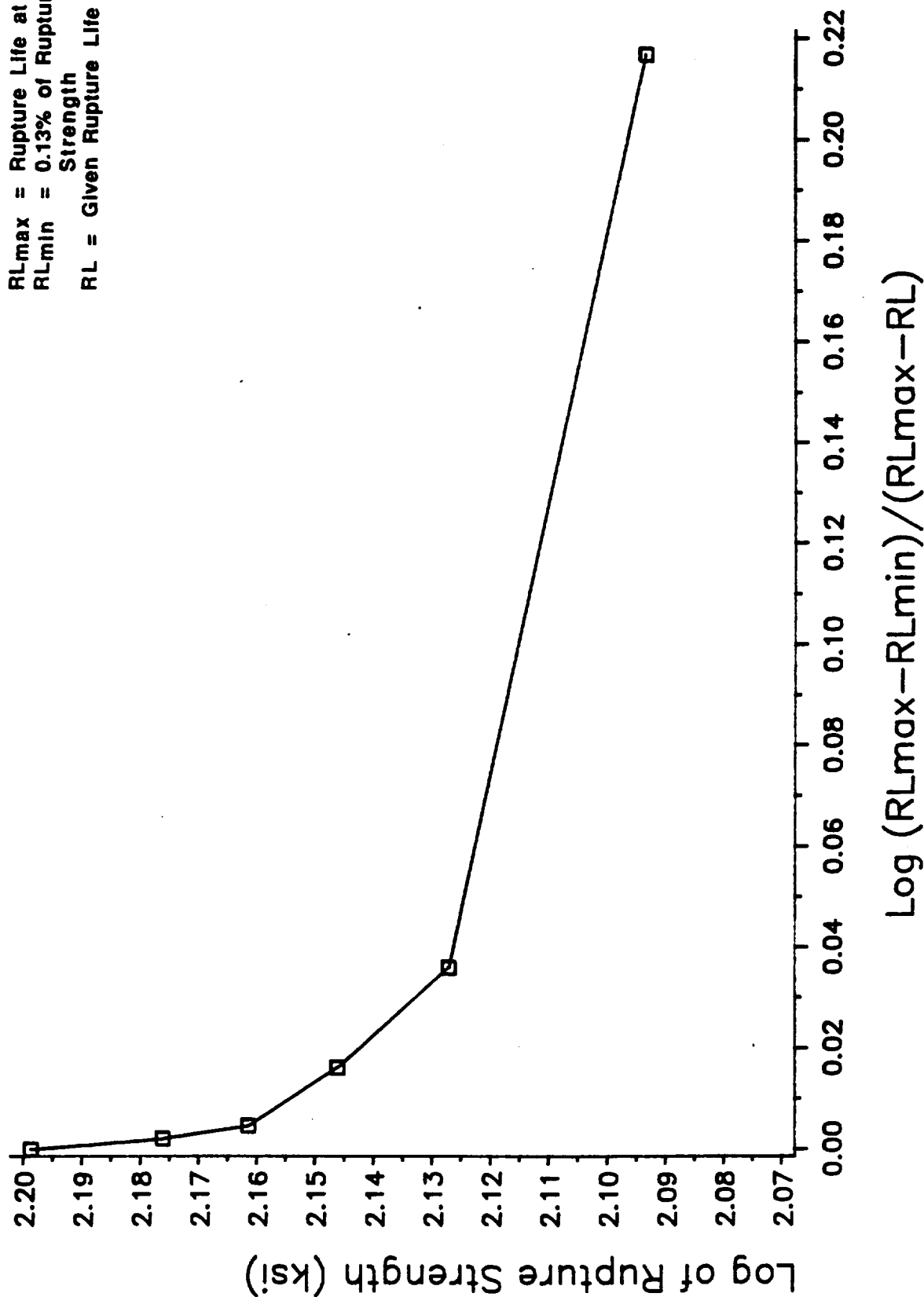


Figure 12 Effect of Time on Rupture Strength for INCONEL 718, Log of Renormalized Data

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8.0 USING BOTH PROMISS AND PROMISC CODES

8.1 Introduction

The PROMISC code can easily be envisioned as a preprocessor to the PROMISS code since it provides the material constants, a_i , either from expert opinion or from experimental data. These constants would then be input to the PROMISS code and used to predict strength. A number of precautions should be exercised by investigators using these codes in this manner. These precautions are explained in the following section.

8.2 PROMISC - PROMISS Interface

Before using PROMISC-generated material constants as input to PROMISS, the diagnostics provided in the PROMISC output must be checked for violation of assumptions. For example, the user needs to verify that the R-squared value and the p-value for regression in the ANOVA Table are adequate to justify the validity of the regression model. If the value of R-squared is too small then the multiple linear regression equation used in PROMISC has little or no predictive capability. Then, the user needs to glean insignificant effects or primitive variables from the multifactor interaction equation. The significance of an effect can be determined from the column of p-values in the Sequential Statistics Table. If the user does not remove insignificant variables, then the multifactor interaction equation, used in PROMISS, would have an extra product term due to an extraneous regressor variable. Also, the user needs to scrutinize the Case Analysis Table for the presence of outliers by examining the column which contains Cook's Distance. The presence of an outlier can inordinately influence the regression coefficients which are the exponents in the multifactor interaction equation (i.e., material constants, a_i). If these regression coefficients change markedly, then so will the PROMISS-predicted strength. Finally, the user should test the residuals from the Case Analysis Table to see if they are normally distributed. This analysis can be completed through the Shapiro-Wilk test. If the residuals are not normal, then a transformation of the regression variables (effects or primitive variables) may be indicated. Once the user has positively answered the previous four caveats, then predicting strength using PROMISS from the multiple linear regression equation in PROMISC is valid. Further details are available in Section 11.0, APPENDIX 2 (Sections 3.1.1 and 3.2.1, Discussion of Results).

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PROMISS USER MANUAL

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Thomas B. Lovelace**

**APPENDIX 1
of Final Technical Report
of Project Entitled
Development of Advanced Methodologies
for Probabilistic Constitutive Relationships
of Material Strength Degradation Models, Phase 2**

NASA Grant No. NAG 3-867, Supp. 2

Prepared for:

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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**The Division of Engineering
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January, 1990**

Vers. 2.0

1.0 INTRODUCTION

This User Manual documents the FORTRAN program PROMISS (Vers. 2.0). The program determines the random strength of an aerospace propulsion component, due to a number of diverse random effects (see Section 2.0, Theoretical Background).

Included in this User Manual are details regarding the theoretical background of PROMISS, input data instructions and sample problems illustrating the use of both PROMISS and PROMISC. APPENDIX A gives information on the primitive variables, their symbols, FORTRAN names and both SI and U.S. Customary units. APPENDIX B includes a disk containing the actual input and output files corresponding to the sample problems. The source code is available from the first author at the address given on the cover page of this report. APPENDIX C details the IMSL, Version 10 [1], subroutines and functions called by PROMISS. APPENDIX D illustrates SAS/GRAPH [2] programs that can be used to plot both the probability density functions (p.d.f.) and the cumulative distribution functions (c.d.f.).

2.0 THEORETICAL BACKGROUND

Recently, a general phenomenological constitutive relationship, for composite materials subjected to a number of diverse effects or primitive variables, has been postulated to predict mechanical and thermal material properties [3,4,5,6]. The resulting multifactor interaction constitutive equations summarize composite micromechanics theory and have been used to predict material properties for a unidirectional fiber-reinforced lamina, based on the corresponding properties of the constituent materials.

These equations have been modified to predict the mechanical property of strength for one constituent material due to "n" diverse effects or primitive variables. These effects could include both time-independent and time-integrated primitive variables, such as mechanical stresses subjected to both static and impact loads, thermal stresses due to temperature variations and thermal shock, and other effects such as chemical reaction or radiation attack. They might also include other time-dependent primitive variables such as creep, mechanical fatigue, thermal aging, thermal fatigue, or even effects such as seasonal attack (see APPENDIX A, Primitive Variables, Symbols, and Units). For most of these primitive variables, strength has been observed to decrease with an increase in the variable.

The postulated constitutive equation accounts for the degradation of strength due to these primitive variables. The general form of the equation is

$$\frac{S}{S_0} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{i0}} \right]^{a_i} \quad (1)$$

where A_i , A_{iF} and A_{i0} are the current, ultimate and reference values of a particular effect, a_i is the value of an empirical constant for the i^{th} effect or primitive variable, n is the number of product terms of primitive variables in the model, and S and S_0 are the current and reference values of material strength. Each term has the property that if the current value equals the ultimate value, the current strength will be zero. Also, if the current value equals the reference value, the term equals one and strength is not affected by that variable.

This deterministic constitutive model may be calibrated by an appropriately curve-fitted least squares multiple linear regression of experimental data [7], perhaps supplemented by expert opinion. Ideally, experimental data giving the relationship between effects and strength is obtained. For example, data for just one effect could be plotted on log-log paper. A good fit for the data is then obtained by a linear regression analysis. This is illustrated schematically in Figure 1. The postulated constitutive equation, for a single

effect, is then obtained by noting the linear relation between $\log S$ and $\log \left[\frac{A_F - A_0}{A_F - A} \right]$,

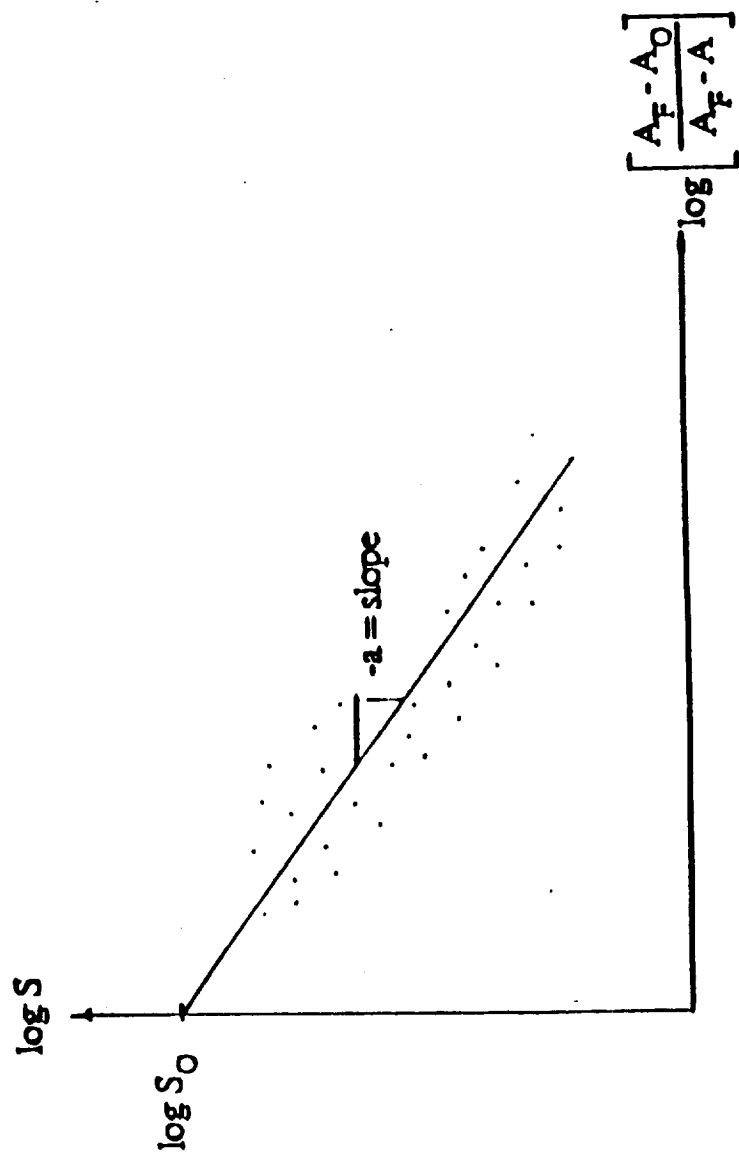


Fig. 1 Schematic of experimental data illustrating the effect of one primitive variable on strength.

as follows:

$$\begin{aligned}
 \log S &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] + \log S_O \\
 \log S - \log S_O &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \log \frac{S}{S_O} &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \frac{S}{S_O} &= \left[\frac{A_F - A_O}{A_F - A} \right]^{-a} \\
 \frac{S}{S_O} &= \left[\frac{A_F - A}{A_F - A_O} \right]^a
 \end{aligned} \tag{2}$$

Note that the above equation (2) is for a primitive variable that lowers strength. If a variable raises strength, the exponent is negative.

This general constitutive model may be used to estimate the strength of an aerospace propulsion system component under the influence of a number of diverse effects or primitive variables. The probabilistic treatment of this equation includes randomizing the deterministic multifactor interaction constitutive equation, performing probabilistic analysis by simulation and generating probability density function (p.d.f.) estimates for strength using a non-parametric method, maximum penalized likelihood [8,9]. Integration yields the cumulative distribution function (c.d.f.) from which probability statements regarding strength may be made. This probabilistic constitutive model predicts the random strength of an aerospace propulsion component due to a number of diverse random effects.

This probabilistic constitutive model is embodied in two FORTRAN programs, PROMISS (Probabilistic Material Strength Simulator) and PROMISC (Probabilistic Material Strength Calibrator); see Final Technical Report, APPENDIX 2. PROMISS calculates the random strength of an aerospace propulsion component due to as many as eighteen diverse random effects. Results are presented in the form of probability density functions and cumulative distribution functions of normalized strength, S/S_O . PROMISC calculates the values of the empirical material constants, a_i .

PROMISS includes a relatively simple "fixed" model as well as a "flexible" model. The fixed model postulates a probabilistic constitutive equation that considers the primitive variables given in Table 1. The general form of this constitutive equation is given in equation (1), wherein there are now $n = 7$ product terms, one for each effect or primitive variable listed above. Note that since this model has seven primitive variables, each containing four values of the variable, it has a total of twenty-eight variables. The flexible model postulates a probabilistic constitutive equation that considers up to as many as $n = 18$ product terms for primitive variables. These variables may be selected to utilize the theory and experimental data currently available for the specific strength degradation mechanisms of interest. The specific effects included in the flexible model are listed in Table 2. Note that in order to provide for future expansion and customization of the flexible model, six "other" effects have been provided.

Table 1 Primitive variables available in the fixed model

jth Primitive Variable	Primitive Variable Type
1	Stress due to static load
2	Temperature
3	Chemical reaction
4	Stress due to impact
5	Mechanical fatigue
6	Thermal fatigue
7	Creep

Table 2 Primitive variables available in the flexible model

A. Environmental Effects

1. Mechanical
 - a. Stress
 - b. Impact
 - c. Other Mechanical Effect
2. Thermal
 - a. Temperature Variation
 - b. Thermal Shock
 - c. Other Thermal Effect
3. Other Environmental Effects
 - a. Chemical Reaction
 - b. Radiation Attack
 - c. Other Environmental Effect

B. Time-Dependent Effects

1. Mechanical
 - a. Creep
 - b. Mechanical Fatigue
 - c. Other Mech. Time-Dep. Effect
2. Thermal
 - a. Thermal Aging
 - b. Thermal Fatigue
 - c. Other Thermal Time-Dep. Effect
3. Other Time-Dependent Effects
 - a. Corrosion
 - b. Seasonal Attack
 - c. Other Time-Dep. Effect

The considerable scatter of experimental data and the lack of an exact description of the underlying physical processes for the combined mechanisms of fatigue, creep, temperature variations, and so on, make it natural, if not necessary to consider probabilistic models for a strength degradation model. Therefore, the fixed and flexible models corresponding to equation (1) are "randomized", and yield the "random normalized material strength due to a number of diverse random effects or primitive variables." Note that for the fixed model, equation (1) has the following form:

$$S/S_0 = f(A_{1F}, A_1, A_{10}, A_{2F}, A_2, A_{20}, \dots, A_{7F}, A_7, A_{70}) \quad (3)$$

where A_i , A_{iF} and A_{i0} are the ultimate, current and reference values of the i^{th} of seven effects or primitive variables as given in Table 1. In general, this expression can be written as,

$$S/S_0 = f(X_i), i = 1, \dots, 28, \quad (4)$$

where the X_i are the twenty eight independent variables in equation (3). Thus, the fixed model is "randomized" by assuming all the independent variables, X_i , $i = 1, \dots, 28$, to be random and stochastically independent. For the flexible model, equation (1) has a form analogous to equations (3) and (4), except that there are as many as seventy-two independent variables. Applying probabilistic analysis to either of these randomized equations yields the distribution of the dependent random variable, normalized material strength, S/S_0 .

Although a number of methods of probabilistic analysis are available, [8] simulation was chosen for PROMISS. Simulation utilizes a theoretical sample generated by numerical techniques for each of the independent random variables. One value from each sample is substituted into the functional relationship, equation (3), and one realization of normalized strength, S/S_0 , is calculated. This calculation is repeated for each value in the set of samples, yielding a distribution of different values for normalized strength.

A probability distribution function is generated from these different values of normalized strength, using a non-parametric method, maximum penalized likelihood. Maximum penalized likelihood generates the p.d.f. estimate using the method of maximum likelihood together with a penalty function to smooth it [9]. Finally, integration of the generated p.d.f. results in the cumulative distribution function, from which probabilities of normalized strength can be directly observed.

PROMISS includes computational algorithms for both the fixed and the flexible probabilistic constitutive models. As described above, PROMISS randomizes the following equation:

$$\frac{S}{S_0} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{i0}} \right]^{a_i} \quad (5)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_i , A_{iF} and A_{iO} are random variables, a_i is the i^{th} empirical material constant and S/S_O is normalized strength. There are a maximum of eighteen possible effects or primitive variables that may be included in the model. For the flexible model option, they may be chosen by the user from those in Table 2. For the fixed model option, the primitive variables of Table 1 are chosen. Within each primitive variable term the current, ultimate and reference values and the empirical material constant may be modeled as either deterministic (empirical, calculated by PROMISC), normal, lognormal, or Weibull random variables. Simulation is used to generate a set of realizations for normalized random strength, S/S_O , from a set of realizations for primitive variables and empirical material constants. Maximum penalized likelihood is used to generate an estimate for the p.d.f. of normalized strength, from a set of realizations of normalized strength. Integration of the p.d.f. yields the c.d.f. Plot files are produced to plot both the p.d.f. and the c.d.f. PROMISS also provides information on S/S_O statistics (mean, variance, standard deviation and coefficient of variation). A resident database, for database rather than user input of empirical material constants, is also provided.

PROMISC (see Final Technical Report, APPENDIX 2) performs a multiple linear regression on actual experimental or simulated experimental data for as many as eighteen effects or primitive variables, yielding regression coefficients that are the empirical material constants, a_i , required by PROMISS. It produces the multiple linear regression of the log transformation of equation (3), the PROMISS equation. When transformed it becomes

$$\log \frac{S}{S_O} = \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (6)$$

or

$$\log S = \log S_O + \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (7)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_i , A_{iF} and A_{iO} are primitive variable data and a_i is the i^{th} empirical material constant, or the i^{th} regression coefficient to be predicted by PROMISC. Also, $\log S_O$ is the log transformed reference value of strength, or the intercept regression coefficient to be predicted by PROMISC, and $\log S$ is the log transformed strength.

Experimental data for up to eighteen possible effects, as given in Table 2, may be included. The primitive variable data may be either actual experimental data or expert opinion, directly read from input, or simulated data where expert opinion is specified as the mean and standard deviation of a normal or lognormal distribution. The simulated data option for input data was used in the early stages of code development to verify correct performance. The input data, whether actual or simulated, is read in and assembled into a data matrix. From this data matrix, a corrected sums of squares and crossproducts matrix is computed. From this sums of squares and crossproducts matrix, and a least squares methodology, a multiple linear regression is performed to calculate estimates for the empirical material constant, a_i , and the reference strength, S_0 . These are the regression coefficients.

PROMISC includes enhancements of the multiple linear regression analysis to screen data from "outliers" and collinearities, determine "how well" the data fit the regression, quantify the importance and relative importance of each factor in the postulated constitutive equation, eq. (1), as well as check assumptions inherent in the use of multiple linear regression. Further details are provided in the Final Technical Report, Section 6.0, NASA Grant No. NAG 3-867, Supp. 2, "Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation."

3.0 SAMPLE PROBLEMS, DATA INPUT, AND DISCUSSION OF RESULTS

Data input for PROMISS is user friendly and easy to enter. Data can be directly input by the user or the user can select data to be input by the program from its own resident database. Several examples follow (see also Section 6.0, APPENDIX B).

3.1 PROMISS Input for Flexible Model with No Statistical Distribution (Deterministic) and No use of the Resident Database

The 1st line of input (format 2E12.4, see item 1, below) determines the random number generator seed and the data sample size. The 2nd line (format I3, see item 2, below) determines either a fixed or a flexible model. The 3rd through 8th lines of input (format I3,2X,I3,2X,I3, see item 3, below) choose the 18 effects for the flexible model. On the 9th line of input (format I3, see item 4, below), the user chooses if the data is to be read from the user input or the database. The 10th line (format I3,2X,I3,2X,I3, 2X,I3, see item 4b below) determines the nature of the effect or primitive variable (deterministic or random). The 11th through 14th lines (format 10X,D12.4, see items 4b to 22, below) specify values for the effect or primitive variable. This sequence of five input lines (i.e., 9 to 14) repeats for the other effects selected (see items 5 to 21). A table listing the primitive variables, their units and symbols is given in Section 5.0, APPENDIX A. Finally, IMSL subroutine parameters are entered as indicated in items 23 and 24.

1. Line 1 selects the Random Number Generator Seed (ISEED) and Sample Size (NTOT).

EXAMPLE:

```
12345678901234567890*
 1          40
```

2. Line 2 selects either Fixed or Flexible Model (MODEL = 0 is flexible, MODEL = 1 is fixed).

EXAMPLE:

```
12345678901234567890
 0
```

3. Lines 3 to 8 select the 18 effects for the Flexible Model where:

EFFMS = 1 is Quasi-static Stress Effect
EFFMS = 0 is No Quasi-static Stress Effect
EFFMI = 1 is Impact Effect
EFFMI = 0 is No Impact Effect

* NOTE: the ruler is to aid the user in formatting and is not a part of the input.

EFFMO = 1 is Other Mechanical Effect
EFFMO = 0 is No Other Mechanical Effect

EFFTT = 1 is Temperature Effect
EFFTT = 0 is No Temperature Effect
EFFTS = 1 is Thermal Shock Effect
EFFTS = 0 is No Thermal Shock Effect
EFFTO = 1 is Other Thermal Effect
EFFTO = 0 is No Other Thermal Effect

EFFOC = 1 is Chemical Effect
EFFOC = 0 is No Chemical Effect
EFFOR = 1 is Radiation Effect
EFFOR = 0 is No Radiation Effect
EFFOO = 1 is Other Effect
EFFOO = 0 is No Other Effect

TEFFMC = 1 is Creep Effect
TEFFMC = 0 is No Creep Effect
TEFFMF = 1 is Mechanical Fatigue Effect
TEFFMF = 0 is No Mechanical Fatigue Effect
TEFFMO = 1 is Other Time-Dependent Mechanical Effect
TEFFMO = 0 is No Other Time-Dependent Mechanical Effect

TEFFTA = 1 is Thermal Aging Effect
TEFFTA = 0 is No Thermal Aging Effect
TEFFTF = 1 is Thermal Fatigue Effect
TEFFTF = 0 is No Thermal Fatigue Effect
TEFFTO = 1 is Other Time-Dependent Thermal Effect
TEFFTO = 0 is No Other Time-Dependent Thermal Effect

TEFFOC = 1 is Corrosion Effect
TEFFOC = 0 is No Corrosion Effect
TEFFOS = 1 is Seasonal Attack Effect
TEFFOS = 0 is No Seasonal Attack Effect
TEFFOO = 1 is Other Time-Dependent Effect
TEFFOO = 0 is No Other Time-Dependent Effect.

The effects are read from the input file as follows:

EFFMS, EFFMI, EFFMO
EFFTT, EFFTS, EFFTO
EFFOC, EFFOR, EFFOO
TEFFMC, TEFFMF, TEFFMO
TEFFTA, TEFFTF, TEFFTO
TEFFOC, TEFFOS, TEFFOO.

12345678901234567890

4a. Line 9 selects either User Input or Resident Database for the Exponent for Quasi-static Stress Effect (DATA = 0 is user input , DATA = 1 is database).

12345678901234567890

4b. Line 10 specifies the *nature* of the four variables within the effect by using flags. The flag names are AFDS, ADS, AODS, and SADS. Setting a flag to 0 indicates a deterministic or nominal value will be input for the variable. Setting a flag to 1 indicates a normal distribution. Setting a flag to 2 indicates a lognormal distribution. Setting a flag to 3 indicates a special distribution not yet developed. Setting a flag to 4 indicates a Weibull distribution. Lines 11 to 14 give the values of the four variables. The Quasi-static Stress Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

123456789012345678901234567890

5. Lines 15 to 20 input data for the Impact Effect in the same manner as was described for the Quasi-static Stress Effect (see items 4a and 4b, above). The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

123456789012345678901234567890

47

6. Lines 21 to 26 input data for the Other Mechanical Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Mechanical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```

7. Lines 27 to 32 input data for the Temperature Effect in the same manner as was described for the Quasi-static Stress Effect. The Temperature Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```

8. Lines 33 to 38 input data for the Thermal Shock Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Shock Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```


9. Lines 39 to 44 input data for the Other Thermal Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Thermal Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```

10. Lines 45 to 50 input data for the Chemical Effect in the same manner as was described for the Quasi-static Stress Effect. The Chemical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```

11. Lines 51 to 56 input data for the Radiation Effect in the same manner as was described for the Quasi-static Stress Effect. The Radiation Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                   3.855D+00
                   4.0D+00
                   1.0D+00

```

12. Lines 57 to 62 input data for the Other Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                 3.855D+00
                 4.0D+00
                 1.0D+00

```

13. Lines 63 to 68 input data for the Creep Effect in the same manner as was described for the Quasi-static Stress Effect. The Creep Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                 3.855D+00
                 4.0D+00
                 1.0D+00

```

14. Lines 69 to 74 input data for the Mechanical Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Mechanical Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
  0
  0      0      0      0
                    5.0D+00
                 3.855D+00
                 4.0D+00
                 1.0D+00

```

15. Lines 75 to 80 input data for the Time-dependent Mechanical Effect in the same manner as was described for the Quasi-static Stress Effect. The Time-dependent Mechanical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
0
0      0      0      0
          5.0D+00
        3.855D+00
          4.0D+00
          1.0D+00

```

16. Lines 81 to 86 input data for the Thermal Aging Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Aging Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
0
0      0      0      0
          5.0D+00
        3.855D+00
          4.0D+00
          1.0D+00

```

17. Lines 87 to 92 input data for the Thermal Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
0
0      0      0      0
          5.0D+00
        3.855D+00
          4.0D+00
          1.0D+00

```

18. Lines 93 to 98 input data for the Other Time-dependent Thermal Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Time-dependent Thermal Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
 0
 0      0      0      0
                5.0D+00
            3.855D+00
            4.0D+00
            1.0D+00

```

19. Lines 99 to 104 input data for the Corrosion Effect in the same manner as was described for the Quasi-static Stress Effect. The Corrosion Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
 0
 0      0      0      0
                5.0D+00
            3.855D+00
            4.0D+00
            1.0D+00

```

20. Lines 105 to 110 input data for the Seasonal Attack Effect in the same manner as was described for the Quasi-static Stress Effect. The Seasonal Attack Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
 0
 0      0      0      0
                5.0D+00
            3.855D+00
            4.0D+00
            1.0D+00

```

21. Lines 111 to 116 input data for the Other Time-dependent Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Time-dependent Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

123456789012345678901234567890
 0
 0      0      0      0
                5.0D+00
            3.855D+00
                4.0D+00
                1.0D+00

```

22. The DESPL [1] parameters are NODE, INIT, ALPHA, EPS, and MAXIT and are entered in that order as follows (line 117):

EXAMPLE:

```

1234567890123456789012345678901234567890
21      0      1.0E+01      1.0E-05      30

```

23. The DESPL[1] parameter, IOPT, is entered as follows (line 118):

EXAMPLE:

```

1234567890
 2

```

3.1.1 Discussion of Results

Execution of PROMISS (source code entitled PROMISS89.FOR) produces an output file that gives numerical results (see Section 6.0, APPENDIX B). Execution also produces plotfiles (see Section 6.0, APPENDIX B). These files are used to plot the X and Y axes of the probability density function (p.d.f.) and the cumulative distribution function (c.d.f.) generated by PROMISS. The plots are drawn from the plotfiles by the SAS/GRAPH graphing program (see Section 8.0, APPENDIX D).

3.2 PROMISS Input for Fixed Model with Various Statistical Distributions and use of the Resident Database

The 1st line of input (format 2E12.4, see item 1, below) determines the random number generator seed and the data sample size. The 2nd line (format I3, see item 2, below) determines either a fixed or a flexible model. On the 3rd line of input the user chooses if the data is to be read from the user input or the resident database (format I3, see item 3, below). The 4th line (format I3,2X,I3,2X,I3, 2X,I3, see item 4, below) determines the nature of the effect or primitive variable (deterministic or random). The 5th through 8th lines specify values for the effect or primitive variable. This sequence of five input lines repeats for the other effects (see items 5 through 10, below). If the word DATABASE is entered in the place of the fourth integer (format I3,2X,I3,2X,I3,2X,A8), the program will read a deterministic value for the exponent from its own Resident Database. A table listing the primitive variables, their units and symbols is given in APPENDIX A. Finally, IMSL subroutine parameters are entered as indicated in items 12 and 13.

1. Line 1 selects Random Number Generator Seed (ISEED) and Sample Size (NTOT).

EXAMPLE:

```
12345678901234567890*  
1          40
```

2. Line 2 determines fixed or flexible model (MODEL = 0 is flexible, MODEL = 1 is fixed).

EXAMPLE:

```
12345678901234567890  
1
```

3. Line 3 determines User Input or Database for the Exponent for Quasi-Static Stress Effect (DATA = 0 is user input, DATA = 1 is database).

EXAMPLE:

```
12345678901234567890  
1
```

* NOTE: the ruler is to aid the user in formatting and is not a part of the input.

4. Line 4 specifies the *nature* of the four variables within the effect by using flags. The flag names are AFDS, ADS, AODS, and SADS. Setting a flag to 0 indicates a deterministic or nominal value will be input for the variable. Setting a flag to 1 indicates a normal distribution. Setting a flag to 2 indicates a lognormal distribution. Setting a flag to 3 indicates a special distribution not yet developed. Setting a flag to 4 indicates a Weibull distribution. Lines 5 to 7 give the values of the four variables. The Quasi-static Stress Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
  4      4      2  DATABASE
                130.0D+00    6.500D+00
                90.0D+00    4.500D+00
                -2.9D+00   -0.145D+00

```

5. Line 8 determines user input or database for the exponent for Impact Effect. Lines 9 to 13 input data for the Impact effect in the same manner as was described for the Quasi-static Stress Effect (see items 3 and 4, above). The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
  0
  4      1      2      4
                1.0D+00    0.003D+00
                0.10D+00    0.003D+00
                0.001D+00  0.00003D+00
                -0.5D+00   -0.015D+00

```

6. Line 14 determines user input or database for the exponent for Temperature Effect. Lines 15 to 19 input data for the Temperature Effect in the same manner as was described for the Quasi-static Stress Effect. The Temperature Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1244567890123456789012345678901234567890
  0
  2      2      1      2
                2732.0D+00  82.000D+00
                1562.0D+00  46.70D+00
                68.0D+00   2.040D+00
                0.50D+00   0.015D+00

```

7. Line 20 determines user input or database for the exponent for Chemical Reaction Effect. Lines 21 to 25 input data for the Chemical Reaction Effect in the same manner as was described for the Quasi-static Stress Effect. The Chemical Reaction Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
0
1      1      1      1
          1.0D+00    0.003D+00
          0.02D+00    0.0006D+00
          0.001D+00  0.00003D+00
          0.50D+00    0.015D+00

```

8. Line 26 determines user input or database for the exponent for Creep Effect. Lines 27 to 30 input data for the Creep Effect in the same manner as was described for the Quasi-static Stress Effect. The Creep Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A. Note that when the DATABASE option is used, the input is only 5 lines long per effect, rather than 6 lines (compare to item 7, above).

EXAMPLE:

```

1234567890123456789012345678901234567890
1
2      4      2  DATABASE
          10000.0D+00  500.00D+00
          105.0D+00   3.15D+00
          0.083D+00   0.0025D+00

```

9. Line 31 determines user input or database for the exponent for Mechanical Fatigue Effect. Lines 32 to 36 input data for the Mechanical Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Mechanical Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
0
2      2      2      1
          7.0D+00    0.700D+00
          3.5D+00    0.350D+00
          1.0D+00    0.100D+00
          0.50D+00    0.015D+00

```


10. Line 37 determines user input or database for the exponent for Thermal Fatigue Effect. Lines 38 to 41 input data for the Thermal Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
 1
 2      2      2  DATABASE
                3.0D+00    0.300D+00
                2.3D+00    0.230D+00
                1.0D+00    0.100D+00

```

11. The DESPL[1] parameters are NODE, INIT, ALPHA, EPS, and MAXIT and are entered in that order as follows (line 42):

EXAMPLE:

```

1234567890123456789012345678901234501234567890
 21      0      1.0E+01    1.0E-05    30

```

12. The DESPL[1] parameter, IOPT, is entered as follows (line 43):

EXAMPLE:

```

1234567890
 2

```

DATABASE INPUT FILE**

```

12345678901234567890
 0.5D+00
 0.5D+00
 0.5D+00

```

3.2.1 Discussion of Results

Execution of PROMISS (source code entitled PROMISS89.FOR) produces an output file that gives numerical results (see Section 6.0, APPENDIX B). Execution also produces plotfiles (see Section 6.0, APPENDIX B). These files are used to plot the X and Y axes of the probability density function (p.d.f.) and the cumulative distribution function (c.d.f.) generated by PROMISS. The plots are drawn from the plotfiles by the SAS/GRAPH graphing program (see Section 8.0, APPENDIX D). These plots for the sample problem are shown in Figures 2 and 3.

** PROMISS, Vers. 2.0, currently has a value of 0.5 for all empirical material constants. This is current expert opinion. These values will be updated as data become available (see Section 6.0).

Effect of Uncertainties in Primitive Variables on Strength Scatter for a Nickel Based Superalloy

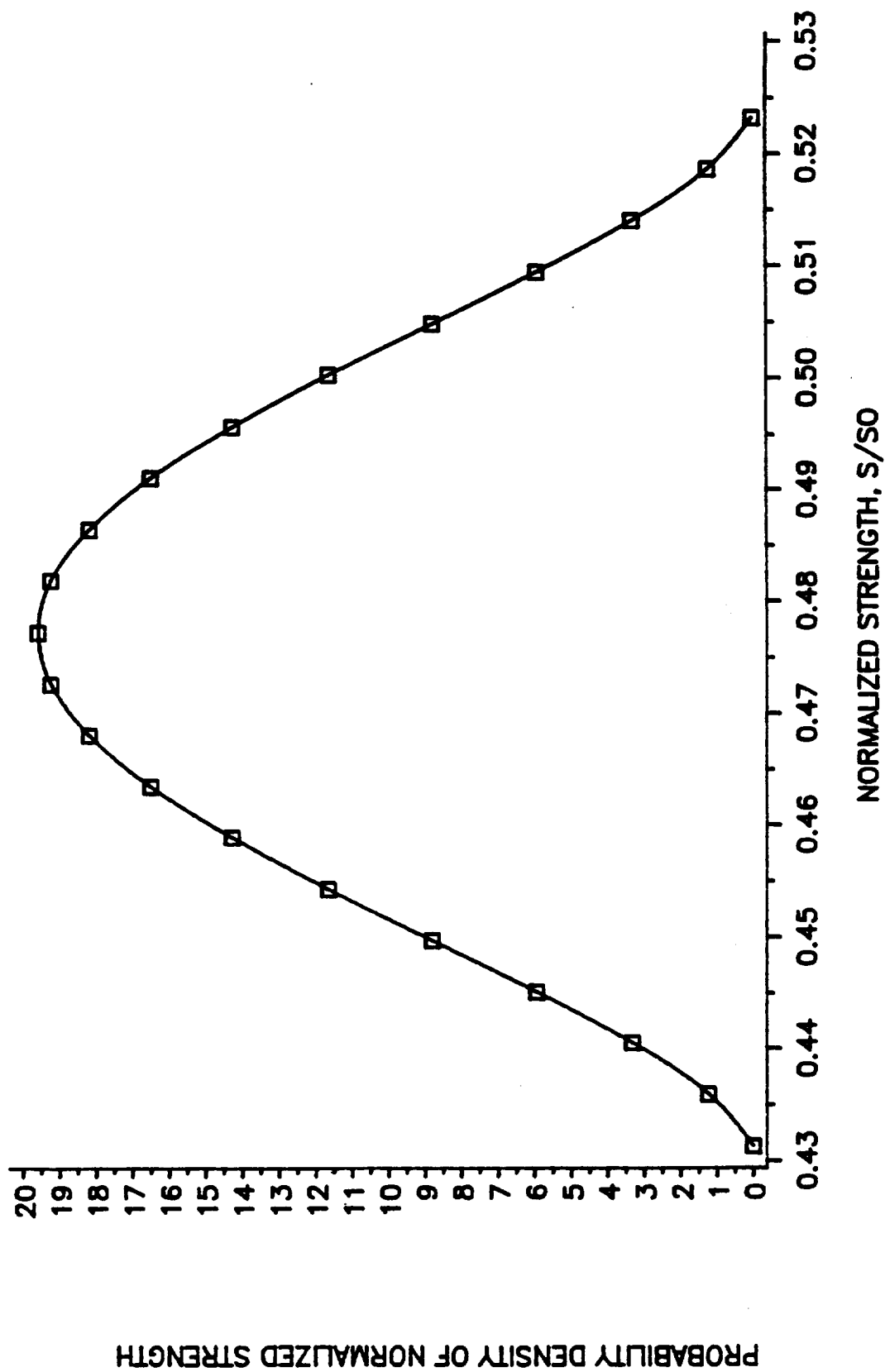


Figure 2 Section 3.2 Example Plot Created Using SAS/GRAPH

Effect of Uncertainties in Primitive Variables on Probable Strength for a Nickel Based Superalloy

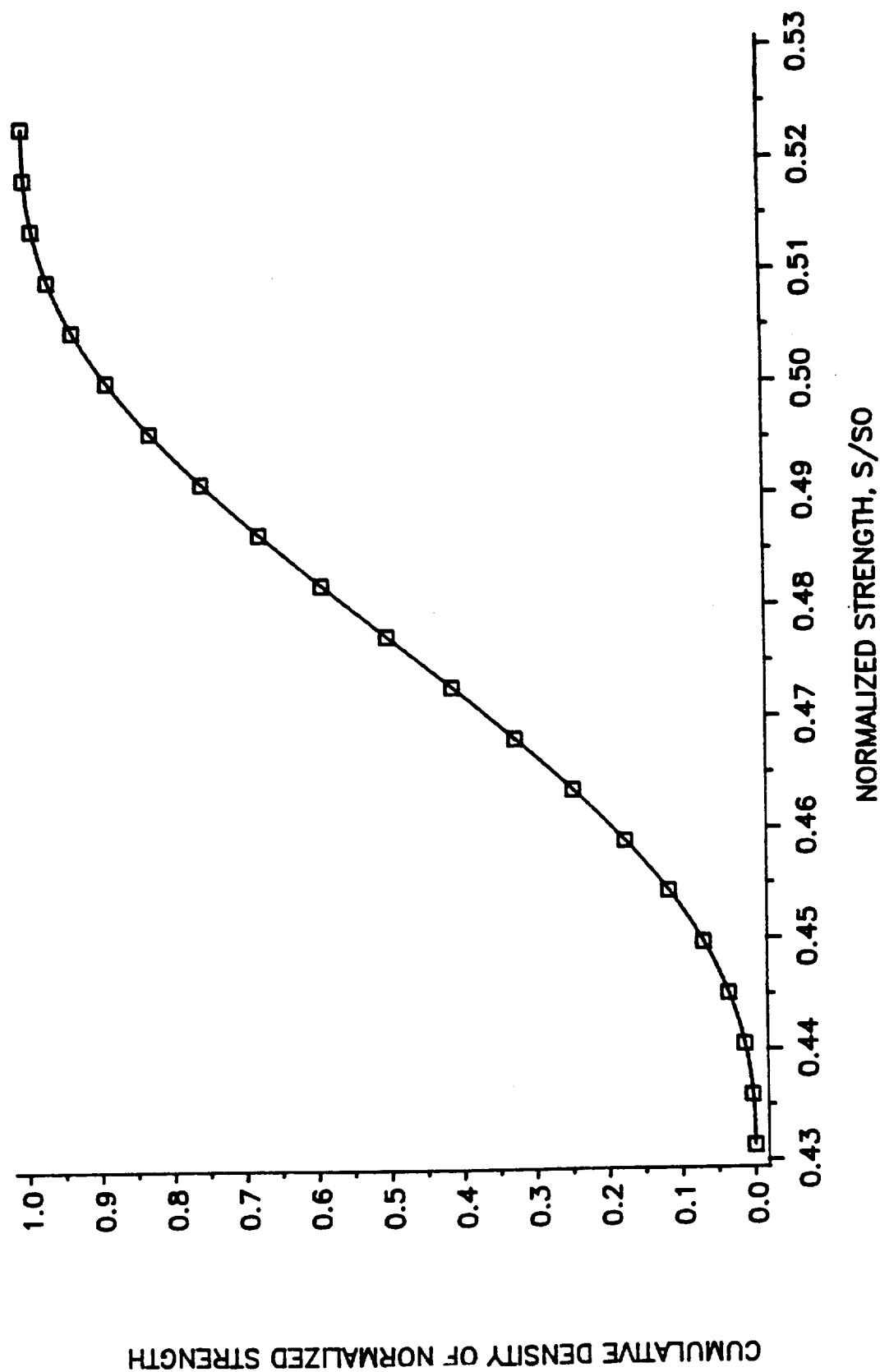


Figure 3 Section 3.2 Example Plot Created Using SAS/GRAPH

3.3 PROMISS Input for Flexible Model with Various Statistical Distributions and Use of the Resident Database

The 1st line of input (format 2E12.4, see item 1, below) determines the random number generator seed and the data sample size. The 2nd line (format I3, see item 2, below) determines either a fixed or a flexible model. The 3rd through 8th lines (format I3,2X,I3,2X,I3, see item 3, below) choose the 18 effects for the flexible model. The 9th line (format I3, see item 4, below) the user chooses if the data is to be read from the user input or the database. The 10th line (format I3,2X,I3,2X,I3, 2X,I3, see item 4, below) determines the nature of the effect or primitive variable. If the word DATABASE is entered in the place of the fourth integer (format I3,2X,I3,2X,I3,2X,A8), the program will read a deterministic value from its own Resident Database. The 11th through 14th lines (format 10X,2D12.4, see item 4, below) specify values for the effect or primitive variable. This sequence of five input lines repeats for the other effects selected (see items 4 through 21, below). A table listing the primitive variables, their units and symbols is given in Section 5.0, APPENDIX A. Finally, IMSL subroutine parameters are entered as indicated in items 23 and 24.

1. Line 1 selects the Random Number Generator Seed (ISEED) and Sample Size (NTOT).

EXAMPLE:

```
12345678901234567890*  
  1      40
```

2. Line 2 determines fixed or flexible model (MODEL = 0 is flexible, MODEL = 1 is fixed).

EXAMPLE:

```
12345678901234567890  
  0
```

3. Lines 3 to 8 select the 18 Effects for the Flexible Model where:

EFFMS = 1 is Quasi-static Stress Effect
EFFMS = 0 is No Quasi-static Stress Effect
EFFMI = 1 is Impact Effect
EFFMI = 0 is No Impact Effect
EFFMO = 1 is Other Mechanical Effect
EFFMO = 0 is No Other Mechanical Effect

EFFTT = 1 is Temperature Effect
EFFTT = 0 is No Temperature Effect
EFFTS = 1 is Thermal Shock Effect
EFFTS = 0 is No Thermal Shock Effect
EFFTO = 1 is Other Thermal Effect
EFFTO = 0 is No Other Thermal Effect

* NOTE: the ruler is to aid the user in formatting and is not a part of the input.

EFFOC = 1 is Chemical Effect
 EFFOC = 0 is No Chemical Effect
 EFFOR = 1 is Radiation Effect
 EFFOR = 0 is No Radiation Effect
 EFFOO = 1 is Other Effect
 EFFOO = 0 is No Other Effect

TEFFMC = 1 is Creep Effect
 TEFFMC = 0 is No Creep Effect
 TEFFMF = 1 is Mechanical Fatigue Effect
 TEFFMF = 0 is No Mechanical Fatigue Effect
 TEFFMO = 1 is Other Time-Dependent Mechanical Effect
 TEFFMO = 0 is No Other Time-Dependent Mechanical Effect

TEFFTA = 1 is Thermal Aging Effect
 TEFFTA = 0 is No Thermal Aging Effect
 TEFFTF = 1 is Thermal Fatigue Effect
 TEFFTF = 0 is No Thermal Fatigue Effect
 TEFFTO = 1 is Other Time-Dependent Thermal Effect
 TEFFTO = 0 is No Other Time-Dependent Thermal Effect

TEFFOC = 1 is Corrosion Effect
 TEFFOC = 0 is No Corrosion Effect
 TEFFOS = 1 is Seasonal Attack Effect
 TEFFOS = 0 is No Seasonal Attack Effect
 TEFFOO = 1 is Other Time-Dependent Effect
 TEFFOO = 0 is No Other Time-Dependent Effect.

The effects are read from the input file as follows:

EFFMS, EFFMI, EFFMO
 EFFTT, EFFTS, EFFTO
 EFFOC, EFFOR, EFFOO
 TEFFMC, TEFFMF, TEFFMO
 TEFFTA, TEFFTF, TEFFTO
 TEFFOC, TEFFOS, TEFFOO.

EXAMPLE:

1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0
1						1				1									
1						1				1									
1						1				1									
1						1				1									
1						1				1									
1						1				1									

4. Line 9 selects either User Input or Resident Database for the Exponent for Quasi-static Stress Effect (DATA = 0 is user input, DATA = 1 is database). Line 10 specifies the *nature* of the four variables within the effect by using flags. The flag names are AFDS, ADS, AODS, and SADS. Setting a flag to 0 indicates a deterministic or nominal value will be input for the variable. Setting a flag to 1 indicates a normal distribution. Setting a flag to 2 indicates a lognormal distribution. Setting a flag to 3 indicates a special distribution not yet developed. Setting a flag to 4 indicates a Weibull distribution. Lines 11 to 14 give the values of the four variables. The Quasi-static Stress Effect variables names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
0
2      4      4      1
          5.0D+00    0.002D+00
          3.855D+00  0.005D+00
          4.0D+00    0.007D+00
          0.51D+00    0.001D+00

```

5. Line 15 determines user input or database for the exponent for Impact Effect. Lines 16 to 19 input data for the Impact effect in the same manner as was described for the Quasi-static Stress Effect (see items 3 and 4, above). The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A. Note that when the DATABASE option is used, the input is 5 lines long per effect, rather than 6 lines (compare to item 4 above).

EXAMPLE:

```

1234567890123456789012345678901234567890
1
4      1      2  DATABASE
          5.0D+00    0.002D+00
          3.855D+00  0.005D+00
          4.0D+00    0.007D+00

```

6. Line 20 determines user input or database for the exponent for Mechanical Effect. Lines 21 to 24 input data for the Mechanical Effect in the same manner as was described for the Quasi-static Stress Effect. The Mechanical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
1
4      4      2  DATABASE
          5.0D+00    0.002D+00
          3.855D+00  0.005D+00
          4.0D+00    0.007D+00

```

7. Line 25 determines user input or database for the exponent for Temperature Effect. Lines 26 to 29 input data for the Temperature Effect in the same manner as was described for the Quasi-static Stress Effect. The Temperature Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
1
1      1      4  DATABASE
                5.0D+00    0.002D+00
                3.855D+00  0.005D+00
                4.0D+00    0.007D+00

```

8. Line 30 determines user input or database for the exponent for Thermal Shock Effect. Lines 31 to 35 input data for the Thermal Shock Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Shock Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
0
4      2      1      2
                5.0D+00    0.002D+00
                3.855D+00  0.005D+00
                4.0D+00    0.007D+00
                0.51D+00    0.001D+00

```

9. Line 36 determines user input or database for the exponent for Other Thermal Effect. Lines 37 to 40 input data for the Other Thermal Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Thermal Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
1
4      2      1  DATABASE
                5.0D+00    0.002D+00
                3.855D+00  0.005D+00
                4.0D+00    0.007D+00

```

10. Line 41 determines user input or database for the exponent for Chemical Reaction Effect. Lines 42 to 45 input data for the Chemical Reaction Effect in the same manner as was described for the Quasi-static Stress Effect. The Chemical Reaction Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
4      1      4  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```

11. Line 46 determines user input or database for the exponent for Radiation Effect. Lines 47 to 50 input data for the Radiation Effect in the same manner as was described for the Quasi-static Stress Effect. The Radiation Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
4      1      4  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```

12. Line 51 determines user input or database for the exponent for Other Effect. Lines 52 to 55 input data for the Other Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
1      4      2  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```


13. Line 56 determines user input or database for the exponent for Creep Effect. Lines 57 to 60 input data for the Creep Effect in the same manner as was described for the Quasi-static Stress Effect. The Creep Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A. The last line for this Effect is eliminated when the database is used.

EXAMPLE:

```

1234567890123456789012345678901234567890
1
1      2      2  DATABASE
                5.0D+00    0.002D+00
                3.855D+00  0.005D+00
                4.0D+00    0.007D+00

```

14. Line 61 determines user input or database for the exponent for Mechanical Fatigue Effect. Lines 62 to 66 input data for the Mechanical Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Mechanical Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
0
1      1      2      1
                5.0D+00    0.002D+00
                3.885D+00  0.005D+00
                4.0D+00    0.007D+00
                0.51D+00    0.001D+00

```

15. Line 67 determines user input or database for the exponent for Other Time-dependent Mechanical Effect. Lines 68 to 71 input data for the Other Time-dependent Mechanical Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Time-dependent Mechanical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
1
2      2      2  DATABASE
                5.0D+00    0.002D+00
                3.855D+00  0.005D+00
                4.0D+00    0.007D+00

```

16. Line 72 determines user input or database for the exponent for Thermal Aging Effect. Lines 73 to 76 input data for the Thermal Aging Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Aging Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
1      1      1  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```

17. Line 77 determines user input or database for the exponent for Thermal Fatigue Effect. Lines 78 to 81 input data for the Thermal Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
4      4      4  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```

18. Line 82 determines user input or database for the exponent for Other Time-dependent Thermal Effect. Lines 83 to 86 input data for the Other Time-dependent Thermal Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Time-dependent Thermal Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A. The last line for this Effect is eliminated when the database is used.

EXAMPLE:

1234567890123456789012345678901234567890

```

1
4      2      2  DATABASE
              5.0D+00    0.002D+00
              3.855D+00  0.005D+00
              4.0D+00    0.007D+00

```

19. Line 87 determines user input or database for the exponent for Corrosion Effect. Lines 88 to 91 input data for the Corrosion Effect in the same manner as was described for the Quasi-static Stress Effect. The Corrosion Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
 1
 1      1      4  DATABASE
                    5.0D+00    0.002D+00
                    3.855D+00  0.005D+00
                    4.0D+00    0.007D+00

```

20. Line 92 determines user input or database for the exponent for Seasonal Attack Effect. Lines 93 to 96 input data for the Seasonal Attack Effect in the same manner as was described for the Quasi-static Stress Effect. The Seasonal Attack Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
 1
 2      4      4  DATABASE
                    5.0D+00    0.002D+00
                    3.855D+00  0.005D+00
                    4.0D+00    0.007D+00

```

21. Line 97 determines user input or database for the exponent for Other Time-dependent Effect. Lines 98 to 101 input data for the Other Time-dependent Effect in the same manner as was described for the Quasi-static Stress Effect. The Other Time-dependent Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

1234567890123456789012345678901234567890
 1
 4      2      4  DATABASE
                    5.0D+00    0.002D+00
                    3.855D+00  0.005D+00
                    4.0D+00    0.007D+00

```


3.4 General PROMISS Program Notes

1. Normalized strength, S/S_0 , is assured to be non-negative; any negative value calculated from input is set arbitrarily to zero.
2. Any effect, $\left[\frac{A_F - A}{A_F - A_0} \right]_i^a$, not included in the model is set to one (1).
3. The IMSL, Vers. 10 subroutine DESPL requires that IMSL subroutine D3SPL be appended to PROMISS for proper operation.
4. Fatigue cycles should be input as log cycles rather than cycles. This assures fatigue affects strength calculations by yielding a fraction significantly below zero. If input for fatigue was in cycles, the value of the effect approaches one, thereby not affecting strength calculations.

4.0 REFERENCES

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4. Hopkins, D.A., "Nonlinear Analysis for High-Temperature Multilayered Fiber Composite Structures," NASA TM 83754, Aug., 1984.
5. Chamis, C.C. and Hopkins, D., "Thermoviscoplastic Nonlinear Constitutive Relationships for Structural Analysis of High Temperature Metal Matrix Composites," NASA TM 87291, Nov., 1985.
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8. Siddall, J.N., "A Comparison of Several Methods of Probabilistic Modeling," Proceedings of the Computers in Engineering Conference, ASME San Diego, CA, Vol. 4, 1982, pp. 231-238.
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5.0 APPENDIX A

PRIMITIVE VARIABLES, SYMBOLS, AND UNITS

Table A1.2 Primitive variables, symbols, and units for PROMISS

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	SI	Units	U.S.
<u>QUASI-STATIC STRESS EFFECT</u>					
Ultimate value	S _{SF}	AF	MPa		ksi
Current value	σ_s	A	MPa		ksi
Reference value	σ_{SO}	AO	MPa		ksi
Material constant	p	SA	Dimensionless		
<u>IMPACT EFFECT</u>					
Ultimate value	S _{DF}	AF2	Dimensionless		
Current value	σ_D	A2	Dimensionless		
Reference value	σ_{DO}	AO2	Dimensionless		
Material constant	s	SA2	Dimensionless		
<u>OTHER MECHANICAL EFFECTS</u>					
Ultimate value	A _{3F}	AF3	Dimensionless		
Current value	A ₃	A3	Dimensionless		
Reference value	A _{3O}	AO3	Dimensionless		
Material constant	a ₃	SA3	Dimensionless		
<u>TEMPERATURE</u>					
Ultimate value	T _F	AF4	°C		°F
Current value	T	A4	°C		°F
Reference value	T _O	AO4	°C		°F
Material constant	q	SA4	Dimensionless		
<u>THERMAL SHOCK</u>					
Ultimate value	A _{5F}	AF5	Dimensionless		
Current value	A ₅	A5	Dimensionless		
Reference value	A _{5O}	AO5	Dimensionless		
Material constant	a ₅	SA5	Dimensionless		

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	SI	Units U.S.
<u>OTHER THERMAL EFFECTS</u>				
Ultimate value	A _{6F}	AF6	Dimensionless	
Current value	A ₆	A6	Dimensionless	
Reference value	A _{6O}	AO6	Dimensionless	
Material constant	a ₆	SA6	Dimensionless	
<u>CHEMICAL EFFECTS</u>				
Ultimate value	R _F	AF7	Dimensionless	
Current value	R	A7	Dimensionless	
Reference value	R _O	AO7	Dimensionless	
Material constant	r	SA7	Dimensionless	
<u>RADIATION EFFECTS</u>				
Ultimate value	A _{8F}	AF8	Dimensionless	
Current value	A ₈	A8	Dimensionless	
Reference value	A _{8O}	AO8	Dimensionless	
Material constant	a ₈	SA8	Dimensionless	
<u>OTHER EFFECTS</u>				
Ultimate value	A _{9F}	AF9	Dimensionless	
Current value	A ₉	A9	Dimensionless	
Reference value	A _{9O}	AO9	Dimensionless	
Material constant	a ₉	SA9	Dimensionless	
<u>CREEP</u>				
Ultimate value	t _{CF}	AF10	Hours	Hours
Current value	t _C	A10	Hours	Hours
Reference value	t _{CO}	AO10	Hours	Hours
Material constant	v	SA10	Dimensionless	
<u>MECHANICAL FATIGUE</u>				
Ultimate value	N _{MF}	AF11	log of cycles	
Current value	N _M	A11	log of cycles	
Reference value	N _{MO}	AO11	log of cycles	
Material constant	t	SA11	Dimensionless	

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	Units SI U.S.
<u>OTHER TIME DEPENDENT MECHANICAL EFFECT</u>			
Ultimate value	A _{12F}	AF12	Dimensionless
Current value	A ₁₂	A12	Dimensionless
Reference value	A _{12O}	AO12	Dimensionless
Material constant	a ₁₂	SA12	Dimensionless
<u>THERMAL AGING</u>			
Ultimate value	A _{13F}	AF13	Dimensionless
Current value	A ₁₃	A13	Dimensionless
Reference value	A _{13O}	AO13	Dimensionless
Material constant	a ₁₃	SA13	Dimensionless
<u>THERMAL FATIGUE</u>			
Ultimate value	N _{TF}	AF14	log of cycles
Current value	N _T	A14	log of cycles
Reference value	N _{TO}	AO14	log of cycles
Material constant	u	SA14	Dimensionless
<u>OTHER TIME- DEPENDENT THERMAL EFFECTS</u>			
Ultimate value	A _{15F}	AF15	Dimensionless
Current value	A ₁₅	A15	Dimensionless
Reference value	A _{15O}	AO15	Dimensionless
Material constant	a ₁₅	SA15	Dimensionless
<u>CORROSION</u>			
Ultimate value	A _{16F}	AF16	Dimensionless
Current value	A ₁₆	A16	Dimensionless
Reference value	A _{16O}	AO16	Dimensionless
Material constant	a ₁₆	SA16	Dimensionless

Primitive Variables (Effect)	Theory Symbol	FORTRAN Name	Units SI	U.S.
---------------------------------	------------------	-----------------	-------------	------

SEASONAL ATTACK

Ultimate value	A _{17F}	AF17	Dimensionless	
Current value	A ₁₇	A17	Dimensionless	
Reference value	A ₁₇₀	AO17	Dimensionless	
Material constant	a ₁₇	SA17	Dimensionless	

OTHER TIME- DEPENDENT EFFECT

Ultimate value	A _{18F}	AF18	Dimensionless	
Current value	A ₁₈	A18	Dimensionless	
Reference value	A ₁₈₀	AO18	Dimensionless	
Material constant	a ₁₈	SA18	Dimensionless	

6.0 APPENDIX B

PROMISS SAMPLE PROBLEM: INPUT AND OUTPUT FILES

Sample problems are discussed in sections 3.1, 3.2, and 3.3. One sample problem corresponds to each section. The input and output file names for each sample problem are listed below. The enclosed disk also includes the same files.

3.1 PROMISS INPUT FOR FLEXIBLE MODEL WITH NO STATISTICAL DISTRIBUTION (DETERMINISTIC) AND NO USE OF THE RESIDENT DATABASE

Input File(s): 31PR.INP
Output File: 31PR.OUT
Plot Files: 31PR1.PLT
31PR2.PLT

3.2 PROMISS INPUT FOR FIXED MODEL WITH VARIOUS STATISTICAL DISTRIBUTIONS AND USE OF THE RESIDENT DATABASE

Input File(s): 32PR1.INP
32PR2.INP
Output File: 32PR.OUT
Plot Files: 32PR1.PLT
32PR2.PLT

3.3 PROMISS INPUT FOR FLEXIBLE MODEL WITH VARIOUS STATISTICAL DISTRIBUTIONS AND USE OF THE RESIDENT DATABASE

Input File(s): 33PR1.INP
33PR2.INP
Output File: 33PR.OUT
Plot Files: 33PR1.PLT
33PR2.PLT

7.0 APPENDIX C

IMSL SUBROUTINE CALLS FROM PROMISS

PROMISS

1. **RNSET** - Initializes a random seed for use in the IMSL random number generators.
2. **RNNOR** - Generates pseudorandom numbers from a standard normal distribution using an inverse CDF method.
3. **RNLNL** - Generates pseudorandom numbers from a lognormal distribution.
4. **RNWIB** - Generates pseudorandom numbers from a Weibull distribution.
5. **DESPL** - Performs nonparametric probability density function estimation by the penalized likelihood method.
6. **GCDF** - Evaluates a general continuous cumulative distribution function given the ordinates of the density.
7. Other IMSL Subroutines - SSCAL and SADD

8.0 APPENDIX D

SAMPLE SAS/GRAPH PROGRAM FOR PROMISS

```
data a;
INFILE 'RAND1.CPR' FIRSTOBS=2;input x y;
GOPTIONS DEVICE=HP7470;
proc gplot;
  axis1 label=(h=1 f=simplex 'LOG OF CYCLES')
        value=(h=1 f=simplex);
  axis2 value=(h=1 f=simplex) label=none;
  plot y*x / haxis=axis1 vaxis=axis2;
  TITLE H=1 A=90 F=SIMPLEX 'PROBABILITY DENSITY FUNCTION';
  symbol i=spline v=square;
data B;
INFILE 'RAND2.CPR' FIRSTOBS=2;input x y;
proc gplot;
  axis1 label=(h=1 f=simplex 'LOG OF CYCLES')
        value=(h=1 f=simplex);
  axis2 value=(h=1 f=simplex) label=none;
  plot y*x / haxis=axis1 vaxis=axis2;
  TITLE H=1 A=90 F=SIMPLEX 'CUMULATIVE DISTRIBUTION FUNCTION';
  symbol i=spline v=square;
```

PROMISC USER MANUAL

Prepared by:

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Thomas B. Lovelace**

**APPENDIX 2
of Final Technical Report
of Project Entitled
Development of Advanced Methodologies
for Probabilistic Constitutive Relationships
of Material Strength Degradation Models, Phase 2**

NASA Grant No. NAG 3-867

Prepared for:

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, OH 44135**

**The Division of Engineering
The University of Texas at San Antonio
San Antonio, TX 78285
January, 1990**

Vers. 2.0

1.0 INTRODUCTION

This User Manual documents the FORTRAN program PROMISC. The program performs a multiple linear regression on actual experimental or simulated experimental data for as many as eighteen effects or primitive variables, yielding regression coefficients that are the empirical material constants, a_j , required by PROMISS (see Section 2.0, Theoretical Background).

Included in this User Manual are details regarding the theoretical background of both PROMISS and PROMISC, input data instructions and sample problems illustrating the use of PROMISC. Appendix A gives information on the primitive variables, their symbols, FORTRAN names and both SI and U.S. Customary units. Appendix B includes a disk containing the actual input and output files corresponding to the sample problems. The source code is available from the author at the address given on the cover page of this report. Appendix C details the IMSL, Version 10 [1], subroutines and functions called by PROMISC.

2.0 THEORETICAL BACKGROUND

Recently, a general phenomenological constitutive relationship for composite materials subjected to a number of diverse effects or primitive variables has been postulated to predict mechanical and thermal material properties [3,4,5,6]. The resulting multifactor interaction constitutive equations summarize composite micromechanics theory and have been used to predict material properties for a unidirectional fiber-reinforced lamina, based on the corresponding properties of the constituent materials.

These equations have been modified to predict the mechanical property of strength for one constituent material due to "n" diverse effects or primitive variables. These effects could include both time-independent and time-integrated primitive variables, such as mechanical stresses subjected to both static and impact loads, thermal stresses due to temperature variations and thermal shock, and other effects such as chemical reaction or radiation attack. They might also include other time-dependent primitive variables such as creep, mechanical fatigue, thermal aging, thermal fatigue, or even effects such as seasonal attack (see Appendix A, Primitive Variables, Symbols, and Units). For most of these primitive variables, strength has been observed to decrease with an increase in the variable.

The postulated constitutive equation accounts for the degradation of strength due to these primitive variables. The general form of the equation is

$$\frac{S}{S_0} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i} \quad (1)$$

where A_i , A_{iF} and A_{iO} are the current, ultimate and reference values of a particular effect, a_i is the value of an empirical constant for the i^{th} effect or primitive variable, n is the number of product terms of primitive variables in the model, and S and S_0 are the current and reference values of material strength. Each term has the property that if the current value equals the ultimate value, the current strength will be zero. Also, if the current value equals the reference value, the term equals one and strength is not affected by that variable.

This deterministic constitutive model may be calibrated by an appropriately curve-fitted least squares multiple linear regression of experimental data [7], perhaps supplemented by expert opinion. Ideally, experimental data giving the relationship between effects and strength is obtained. For example, data for just one effect could be plotted on log-log paper. A good fit for the data is then obtained by a linear regression analysis. This is illustrated schematically in Figure 1. The postulated constitutive equation, for a single

effect, is then obtained by noting the linear relation between $\log S$ and $\log \left[\frac{A_F - A_O}{A_F - A} \right]$,

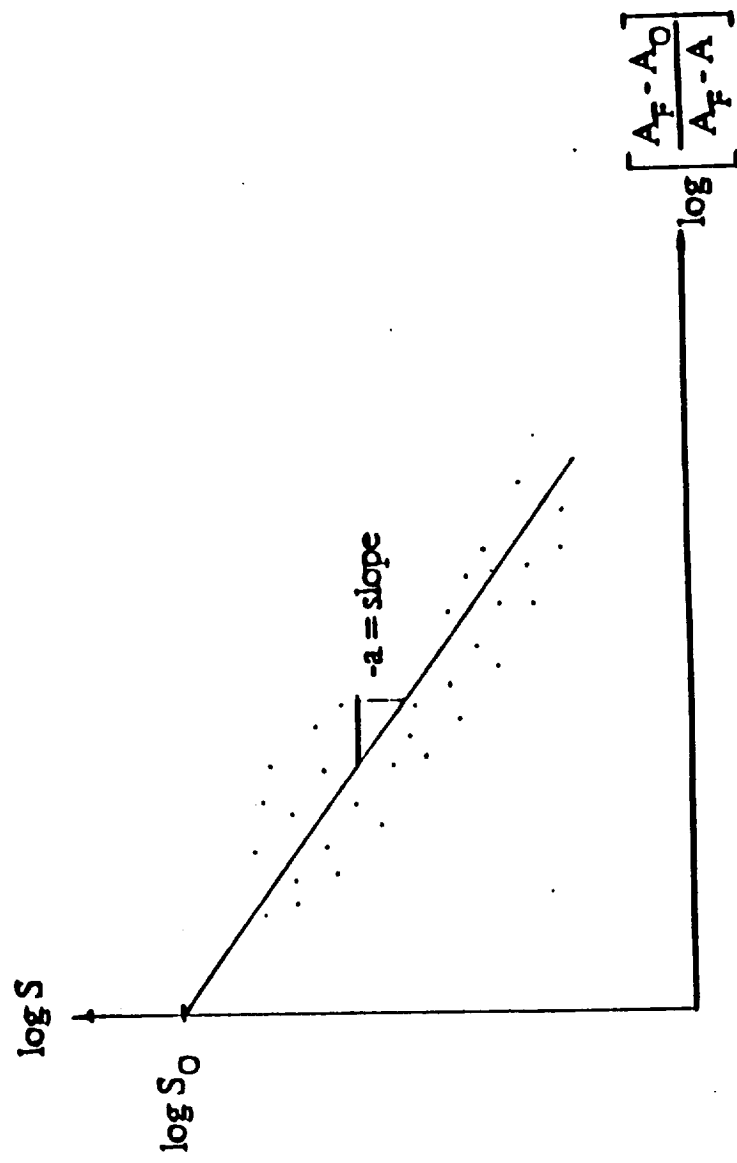


Fig. 1 Schematic of experimental data illustrating the effect of one primitive variable on strength.

as follows:

$$\begin{aligned}
 \log S &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] + \log S_O \\
 \log S - \log S_O &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \log \frac{S}{S_O} &= -a \log \left[\frac{A_F - A_O}{A_F - A} \right] \\
 \frac{S}{S_O} &= \left[\frac{A_F - A_O}{A_F - A} \right]^{-a} \\
 \frac{S}{S_O} &= \left[\frac{A_F - A}{A_F - A_O} \right]^a
 \end{aligned} \tag{2}$$

Note that the above equation (2) is for a primitive variable that lowers strength. If a variable raises strength, the exponent is negative.

This general constitutive model may be used to estimate the strength of an aerospace propulsion system component under the influence of a number of diverse effects or primitive variables. The probabilistic treatment of this equation includes randomizing the deterministic multifactor interaction constitutive equation, performing probabilistic analysis by simulation and generating probability density function (p.d.f.) estimates for strength using a non-parametric method, maximum penalized likelihood [8,9]. Integration yields the cumulative distribution function (c.d.f.) from which probability statements regarding strength may be made. This probabilistic constitutive model predicts the random strength of an aerospace propulsion component due to a number of diverse random effects.

This probabilistic constitutive model is embodied in two FORTRAN programs, PROMISC (Probabilistic Material Strength Calibrator) and PROMISS (Probabilistic Material Strength Simulator); see Final Technical Report, APPENDIX 1. PROMISS calculates the random strength of an aerospace propulsion component due to as many as eighteen diverse random effects. Results are presented in the form of probability density functions and cumulative distribution functions of normalized strength, S/S_O . PROMISC calculates the values of the empirical material constants, a_i .

PROMISS (see Final Technical Report, APPENDIX 1) includes a relatively simple "fixed" model as well as a "flexible" model. The fixed model postulates a probabilistic constitutive equation that considers the primitive variables given in Table 1. The general form of this constitutive equation is given in equation (1), wherein there are now $n = 7$ product terms, one for each effect or primitive variable listed above. Note that since this model has seven primitive variables, each containing four values of the variable, it has a total of twenty-eight variables. The flexible model postulates a probabilistic constitutive equation that considers up to as many as $n = 18$ product terms for primitive variables.

These variables may be selected to utilize the theory and experimental data currently available for the specific strength degradation mechanisms of interest. The specific effects included in the flexible model are listed in Table 2. Note that in order to provide for future expansion and customization of the flexible model, six "other" effects have been provided.

Table 1 Primitive variables available in the fixed model

jth Primitive Variable	Primitive Variable Type
1	Stress due to static load
2	Temperature
3	Chemical reaction
4	Stress due to impact
5	Mechanical fatigue
6	Thermal fatigue
7	Creep

Table 2 Primitive variables available in the flexible model

A. Environmental Effects

1. Mechanical
 - a. Stress
 - b. Impact
 - c. Other Mechanical Effect
2. Thermal
 - a. Temperature Variation
 - b. Thermal Shock
 - c. Other Thermal Effect
3. Other Environmental Effects
 - a. Chemical Reaction
 - b. Radiation Attack
 - c. Other Environmental Effect

B. Time-Dependent Effects

1. Mechanical
 - a. Creep
 - b. Mechanical Fatigue
 - c. Other Mech. Time-Dep. Effect
2. Thermal
 - a. Thermal Aging
 - b. Thermal Fatigue
 - c. Other Thermal Time-Dep. Effect
3. Other Time-Dependent Effects
 - a. Corrosion
 - b. Seasonal Attack
 - c. Other Time-Dep. Effect

The considerable scatter of experimental data and the lack of an exact description of the underlying physical processes for the combined mechanisms of fatigue, creep, temperature variations and so on, make it natural, if not necessary to consider probabilistic models for a strength degradation model. Therefore, the fixed and flexible models corresponding to equation (1) are "randomized", and yield the "random normalized material strength due to a number of diverse random effects or primitive variables." Note that for the fixed model, equation (1) has the following form:

$$S/S_O = f(A_{1F}, A_1, A_{1O}, A_{2F}, A_2, A_{2O}, \dots, A_{7F}, A_7, A_{7O}) \quad (3)$$

where A_i , A_{iF} and A_{iO} are the ultimate, current and reference values of the i^{th} of seven effects or primitive variables as given in Table 1. In general, this expression can be written as,

$$S/S_O = f(X_i), i = 1, \dots, 28, \quad (4)$$

where the X_i are the twenty eight independent variables in equation (3). Thus the fixed model is "randomized" by assuming all the independent variables, X_i , $i = 1, \dots, 28$, to be random and stochastically independent. For the flexible model, equation (1) has a form analogous to equations (3) and (4), except that there are as many as seventy-two independent variables. Applying probabilistic analysis to either of these randomized equations yields the distribution of the dependent random variable, normalized material strength, S/S_O .

Although a number of methods of probabilistic analysis are available, [8] simulation was chosen for PROMISS. Simulation utilizes a theoretical sample generated by numerical techniques for each of the independent random variables. One value from each sample is substituted into the functional relationship, equation (3), and one realization of normalized strength, S/S_O , is calculated. This calculation is repeated for each value in the set of samples, yielding a distribution of different values for normalized strength.

A probability distribution function is generated from these different values of normalized strength using a non-parametric method, maximum penalized likelihood. Maximum penalized likelihood generates the p.d.f. estimate using the method of maximum likelihood together with a penalty function to smooth it [9]. Finally, integration of the generated p.d.f. results in the cumulative distribution function, from which probabilities of normalized strength can be directly observed.

PROMISS includes computational algorithms for both the fixed and the flexible probabilistic constitutive models. As described above, PROMISS randomizes the following equation:

$$\frac{S}{S_O} = \prod_{i=1}^n \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i} \quad (5)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_{iF} , A_{iO} and A_i are random variables, a_i is the i^{th} empirical material constant and S/S_0 is normalized strength. There are a maximum of eighteen possible effects or primitive variables that may be included in the model. For the flexible model option, they may be chosen by the user from those in Table 2. For the fixed model option, the primitive variables of Table 1 are chosen. Within each primitive variable term the current, ultimate and reference values and the empirical material constant may be modeled as either deterministic (empirical, calculated by PROMISC), normal, lognormal, or Weibull random variables. Simulation is used to generate a set of realizations for normalized random strength, S/S_0 , from a set of realizations for primitive variables and empirical material constants. Maximum penalized likelihood is used to generate an estimate for the p.d.f. of normalized strength, from a set of realizations of normalized strength. Integration of the p.d.f. yields the c.d.f. Plot files are produced to plot both the p.d.f. and the c.d.f. PROMISS also provides information on S/S_0 statistics (mean, variance, standard deviation and coefficient of variation). A resident database, for database rather than user input of empirical material constants, is also provided.

PROMISC performs a multiple linear regression on experimental data for as many as eighteen effects or primitive variables, yielding regression coefficients that are the empirical material constants, a_i , required by PROMISS. It produces the multiple linear regression of the log transformation of equation (3), the PROMISS equation. When transformed it becomes

$$\log \frac{S}{S_0} = \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (6)$$

or

$$\log S = \log S_0 + \sum_{i=1}^{18} a_i \log \left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right], \quad (7)$$

where

$$\left[\frac{A_{iF} - A_i}{A_{iF} - A_{iO}} \right]^{a_i}$$

is the i^{th} effect, A_i , A_{iF} and A_{iO} are primitive variable data and a_i is the i^{th} empirical material constant, or the i^{th} regression coefficient to be predicted by PROMISC. Also, $\log S_0$ is the log transformed reference value of strength, or the intercept regression

coefficient to be predicted by PROMISC, and $\log S$ is the log transformed strength. Experimental data for up to eighteen possible effects, as given in Table 2, may be included. The primitive variable data may be either actual experimental data or expert opinion, directly read from input, or simulated data where expert opinion is specified as the mean and standard deviation of a normal or lognormal distribution. The simulated data option for input data was used in the early stages of code development to verify correct performance. The input data, whether actual or simulated, is read in and assembled into a data matrix. From this data matrix, a corrected sums of squares and crossproducts matrix is computed. From this sums of squares and crossproducts matrix, and a least squares methodology, a multiple linear regression is performed to calculate estimates for the empirical material constant, a_i , and the reference strength, S_0 . These are the regression coefficients.

PROMISC includes enhancements of the multiple linear regression analysis to screen data from "outliers" and collinearities, determine "how well" the data fit the regression, quantify the importance and relative importance of each factor in the postulated constitutive equation, eq. (1), as well as check assumptions inherent in the use of multiple linear regression. Further details are provided in the Final Technical Report, Section 6.0, NASA Grant No. NAG 3-867, Supp. 2, "Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation."

3.0 SAMPLE PROBLEMS AND INPUT DATA

Data input for PROMISC is user friendly and easy to enter. Actual experimental data can be input by the user or the user can select simulated experimental data. Two examples follow (see also Section 6.0, Appendix B).

3.1 PROMISC Input For Fixed Model With Actual Experimental Data (40 Data Points)

The 1st line of input (format 2E12.4, see item 1 below) determines the random number generator seed* and the data sample size. The 2nd line (format I3) determines either a fixed or a flexible model. The 3rd line (format I3) chooses the dependent variable as strength. The 4th line (format I3,2X,I3,2X,I3) determines the source of the data (actual experimental, normal or lognormal simulated data). The 5th through the 28th lines (format 5D12.4) specify the data for the primitive variables. This sequence of twenty-five lines repeats for the other primitive variables. Lastly, the 179th through the 187th lines specify the data for the strength variable. A table listing the primitive variables, their units and symbols is given in Section 5.0, Appendix A. IMSL parameters are entered as indicated in items 12 and 13.

1. Line 1 selects the Random Number Generator Seed (ISEED) and Sample Size (NTOT)

EXAMPLE:

```
12345678901234567890**  
1          40
```

2. Line 2 selects either Fixed or Flexible Model (MODEL = 0 is flexible, MODEL = 1 is fixed).

EXAMPLE:

```
12345678901234567890  
1
```

3. Line 3 selects strength as the dependent variable (DEPV = 1 is strength dependent variable, DEPV = 0 is not strength dependent variable).

EXAMPLE:

```
12345678901234567890  
1
```

* If actual experimental data are used (AFDS = 0; ADS = 0; AODS = 0) the random number generator seed, ISEED, is read in but not used in the program.

** NOTE: the ruler is to aid the user in formatting and is not a part of the input.

4a. Line 4 specifies the *source* of the data for the three variables within the Quasi-static Stress Effect by using flags. The flag names are AFDS, ADS and AODS. Setting a flag to 0 indicates actual experimental data is directly read from input. Setting a flag to 1 indicates simulated experimental data, normally distributed, is generated by the program via a random number generator. Setting a flag to 2 indicates simulated experimental data, lognormally distributed, is generated by the program via a random number generator. Setting a flag to 3 indicates data not available.

EXAMPLE:

```
12345678901234567890
  0      0      0
```

4b. Lines 5 to 28 contain the actual experimental data for the three variables within the Quasi-static Stress Effect. The Quasi-static Stress Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
123456789012345678901234567890123456789012345678901234567890
  0.1179D+03  0.1344D+03  0.1273D+03  0.1260D+03  0.1403D+03
  0.1292D+03  0.1295D+03  0.1241D+03  0.1265D+03  0.1229D+03
  0.1321D+03  0.1387D+03  0.1370D+03  0.1264D+03  0.1323D+03
  0.1278D+03  0.1269D+03.....etc.
```

(All of the values for this and other effects are too numerous to include in this description. See Section 6.0 APPENDIX B.)

5. Lines 29 to 53 input data for the Impact Effect in the same manner as was described for the Quasi-static Stress Effect. The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
12345678901234567890
  0      0      0
  0.9870D+00  0.9966D+00  0.1002D+01  0.9997D+00  0.1000D+01
  0.9977D+00  0.9950D+00  0.1001D+01  0.1001D+01  0.1005D+01
  0.9991D+00  0.1000D+01  0.1003D+01  0.9945D+00  0.9952D+00
  0.1000D+00  0.1001D+01.....etc.
```


6. Lines 54 to 78 input data for the Temperature Effect in the same manner as was described for the Quasi-static Stress Effect. The Temperature Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

12345678901	23456789012	34567890123	45678901234	56789012345	67890123456	78901234567	89012345678	90123456789	01234567890
0	0	0							
0.2378D+04	0.2640D+04	0.2789D+04	0.2723D+04	0.2739D+04					
0.2668D+04	0.2598D+04	0.2770D+04	0.2770D+04	0.2856D+04					
0.2708D+04	0.2739D+04	0.2811D+04	0.2583D+04	0.2600D+04					
0.2738D+04	0.2768D+04etc.							

7. Lines 79 to 103 input data for the Chemical Effect in the same manner as was described for the Quasi-static Stress Effect. The Chemical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

12345678901	23456789012	34567890123	45678901234	56789012345	67890123456	78901234567	89012345678	90123456789	01234567890
0	0	0							
0.9870D+00	0.9966D+00	0.1002D+00	0.9997D+00	0.1000D+01					
0.9977D+00	0.9950D+00	0.1001D+01	0.1001D+01	0.1005D+01					
0.9991D+00	0.1000D+01	0.1003D+01	0.9945D+00	0.9952D+00					
0.1000D+01	0.1001D+01etc.							

8. Lines 104 to 128 input data for the Creep Effect in the same manner as was described for the Quasi-static Stress Effect. The Creep Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

12345678901	23456789012	34567890123	45678901234	56789012345	67890123456	78901234567	89012345678	90123456789	01234567890
0	0	0							
0.9072D+04	0.1034D+05	0.9792D+04	0.9696D+04	0.1080D+05					
0.9936D+04	0.9959D+04	0.9544D+04	0.9733D+04	0.9450D+04					
0.1016D+05	0.1067D+05	0.1054D+05	0.9723D+04	0.1018D+05					
0.9827D+04	0.9758D+04etc.							

9. Lines 129 to 153 input data for the Impact Effect in the same manner as was described for the Quasi-static Stress Effect. The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
12345678901234567890123456789012345678901234567890
  0      0      0
  0.5749D+01  0.7465D+01  0.6696D+01  0.6565D+01  0.8136D+01
  0.6894D+01  0.6926D+01  0.6362D+01  0.6615D+01  0.6237D+01
  0.7214D+01  0.7947D+01  0.7752D+01  0.6602D+01  0.7235D+01
  0.6744D+01  0.6649D+01.....etc.
```

10. Lines 154 to 178 input data for the Thermal Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
12345678901234567890123456789012345678901234567890
  0      0      0
  0.2464D+01  0.3199D+01  0.2870D+01  0.2813D+01  0.3487D+01
  0.2954D+01  0.2968D+01  0.2727D+01  0.2835D+01  0.2673D+01
  0.3092D+01  0.3406D+01  0.3322D+01  0.2830D+01  0.3101D+01
  0.2890D+01  0.2850D+01.....etc.
```

11a. Line 179 specifies the source of the strength data by using flags. The flag names are AFDS, ADS and AODS. Setting a flag to 0 indicates actual experimental data is directly read from input. Setting a flag to 1 indicates simulated experimental data, normally distributed, is generated by the program via a random number generator. Setting a flag to 2 indicates simulated experimental data, lognormally distributed, is generated by the program via a random number generator. Setting a flag to 3 indicates data not available.

EXAMPLE:

```
1234567890
  0
```

11b. Lines 180 to 187 contain the actual experimental data for strength. The FORTRAN name for strength is STR.

EXAMPLE:

```
12345678901234567890123456789012345678901234567890
  0.1117D+02  0.0855D+02  0.0735D+02  0.0786D+02  0.0774D+02
  0.0831D+02  0.0895D+02  0.0749D+02  0.0749D+02  0.0687D+02
  0.0798D+02  0.0776D+02  0.0719D+02  0.0906D+02  0.0891D+02
  0.0774D+02  0.0751D+02.....etc.
```

12. The CORVC [1] parameters are IDO, LDX, IFRQ, IWT, MOPT, ICOPT, LDCOV, and LDINCD and are entered in that order as follows (line 188):

EXAMPLE:

```
1234567890123456789012345678901234567890
      0  240      0      0      0      1  19  19
```

13. The RCOV [1] parameters are INTCEP, NOND, NDEP, LDCOV, LDB, LSR, and LDSCPE and are entered in that order as follows (line 189):

EXAMPLE:

```
1234567890123456789012345678901234567890
      1      7      1  19  19  19      1
```

3.1.1 Discussion of Results

Execution of PROMISC (source code entitled PROMISC5.FOR) produces an output file that gives computed values for the empirical material constants, a_i . Output also includes statistics and diagnostics that enhance the PROMISC multiple linear regression analysis (see Section 2.0, Theoretical Background and/or Final Technical Report, Section 6 Increased Capability of PROMISC, NASA Grant No. NAG 3-867, Supp. 2, "Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation").

Execution of the PROMISC code for the example problem whose input is specified in Section 3.1 produces an output file that includes regression or least squares estimates of the exponents (empirical material constants, a_i) in the multifactor interaction equation under the heading BBBB. For example, the constant coefficient (y-intercept, $\log S_0$) is predicted to be 0.6717, the exponent for quasi-static stress to be 0.6449, the exponent for impact to be 0.0000, and so on.

To determine "how well" the data fit the regression equation consider the next subheading in the output file, where R-squared is given. R-squared and the Adjusted R-squared columns give the percentage of the variation in the data which can be explained by the multiple linear regression equation. In this example the multiple linear regression equation explains about 99.7% of the variation. An R-squared value of 100% indicates an exact fit, whereas an R-squared value of 0 % indicates no correlation between the independent variable (strength) and any of the regression variables (effects or primitive variables). This is a first assessment of the adequacy of the model.

In the next heading under ANOVA Table, an alternative statistical measure of "how well" the data fit the "complete" multiple linear regression equation is given. This statistical measure is given in the last column headed by "Prob. of Larger F". This term, known as a p-value, gives the probability that the relationship was due to chance alone and not to the multiple linear regression equation. In this case the probability is virtually zero, which corroborates the observations from the R-squared columns. P-values near zero indicate that the multifactor interaction equation is significant. Thus, we conclude that the multiple linear regression equation is quite effective in predicting strength.

Among the seven regression variables (effects or primitive variables) it is desirable to assess the relative importance of each. From the section headed by BBBB or the one headed by "Inference on Coefficients", the estimates of the exponents in the multifactor interaction equation can be viewed. Since the exponent for impact is virtually zero it can be reasonably assumed that this factor does little to predict the strength. However, it is not wise to be misled by the mere size of the coefficients. The statistical terms which one should focus on are the "F-statistic" column and the "Prob. of Larger F" column in the section headed by Sequential Statistics. For the first variable, quasi-static stress, the p-value gives the probability that the factor is not significant in the prediction equation. The exponent for quasi-static stress is 0.6449 and the associated p-value is 0.0660, which indicates quasi-static stress is significant. In most statistical circles, p-values near 0.05 or less are considered significant. Moreover, the sixth effect, mechanical fatigue, has a coefficient (exponent of -0.1248) but its p-value is virtually zero. This result indicates that mechanical fatigue (because of its smaller p-value), has greater predictive capability than the quasi-static stress effect. However, both should be considered significant. The remaining factors are completely insignificant.

In outlier detection, use the "Case Analysis" section and the factor, "Cook's D". Cook's D is given first in the second line of each of the forty cases. For example, for observation 1 Cook's D is 37.7568. The larger the value of Cook's D, the farther the observation is away from the center of the data. We consequently note that observation 14, with a Cook's D of 20.0449, has the smallest value, and observation 34, with Cook's D of 50.3682, has the largest value. However even the largest value is well within acceptable ranges indicating that there are no outliers in the data.

The residual column and the standardized residual column can be used to test the hypothesis that errors are normally distributed. In addition, the remaining columns can be used for many statistical purposes in verifying the assumptions in multiple linear regression.

3.2 PROMISC Input For Fixed Model With Actual Experimental Data (240 Data Points)

The 1st line of input (format 2E12.4, see item 1 below) determines the random number generator seed* and the data sample size. The 2nd line (format I3) determines either a fixed or a flexible model. The 3rd line (format I3) chooses the dependent variable as strength. The 4th line (format I3,2X,I3,2X,I3) determines the source of the data (actual experimental, normal or lognormal simulated data). The 5th through the 148th lines (format 5D12.4) specify the data for the primitive variables. This sequence of one hundred forty-five lines repeats for the other primitive variables. Lastly, the 1019th through the 1067th lines specify the data for the strength variable. A table listing the primitive variables, their units and symbols is given in Section 5.0, Appendix A. IMSL parameters are entered as indicated in items 12 and 13.

1. Line 1 selects the Random Number Generator Seed (ISEED) and Sample Size (NTOT).

EXAMPLE:

```
12345678901234567890**  
1      240
```

2. Line 2 selects either Fixed or Flexible Model (MODEL = 0 is flexible, MODEL = 1 is fixed).

EXAMPLE:

```
12345678901234567890  
1
```

3. Line 3 selects strength as the dependent variable (DEPV = 1 is strength dependent variable, DEPV = 0 is not strength dependent variable).

EXAMPLE:

```
12345678901234567890  
1
```

* If actual experimental data are used (AFDS = 0; ADS = 0; AODS = 0) the random number generator seed, ISEED, is read in but not used in the program.

** NOTE: the ruler is to aid the user in formatting and is not a part of the input.

4a. Line 4 specifies the *source* of the data for the three variables within the Quasi-static Stress Effect by using flags. The flag names are AFDS, ADS and AODS. Setting a flag to 0 indicates actual experimental data is directly read from input. Setting a flag to 1 indicates simulated experimental data, normally distributed, is generated by the program via a random number generator. Setting a flag to 2 indicates simulated experimental data, lognormally distributed, is generated by the program via a random number generator. Setting a flag to 3 indicates data not available.

EXAMPLE:

```
12345678901234567890
 0      0      0
```

4b. Lines 5 to 148 contain the actual experimental data for the three variables within the Quasi-static Stress Effect. The Quasi-static Stress Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
12345678901234567890123456789012345678901234567890
 0.1179D+03  0.1344D+03  0.1273D+03  0.1260D+03  0.1403D+03
 0.1292D+03  0.1295D+03  0.1241D+03  0.1265D+03  0.1229D+03
 0.1321D+03  0.1387D+03  0.1370D+03  0.1264D+03  0.1323D+03
 0.1278D+03  0.1269D+03.....etc.
```

(All of the values for this and other effects are too numerous to include in this description. See Section 6.0 APPENDIX B.)

5. Lines 149 to 293 input data for the Impact Effect in the same manner as was described for the Quasi-static Stress Effect. The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```
12345678901234567890
 0      0      0
 0.9870D+00  0.9966D+00  0.1002D+01  0.9997D+00  0.1000D+01
 0.9977D+00  0.9950D+00  0.1001D+01  0.1001D+01  0.1005D+01
 0.9991D+00  0.1000D+01  0.1003D+01  0.9945D+00  0.9952D+00
 0.1000D+00  0.1001D+01.....etc.
```

6. Lines 294 to 438 input data for the Temperature Effect in the same manner as was described for the Quasi-static Stress Effect. The Temperature Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0      0      0
0.2378D+04 0.2640D+04 0.2789D+04 0.2723D+04 0.2739D+04
0.2668D+04 0.2598D+04 0.2770D+04 0.2770D+04 0.2856D+04
0.2708D+04 0.2739D+04 0.2811D+04 0.2583D+04 0.2600D+04
0.2738D+04 0.2768D+04.....etc.

```

7. Lines 439 to 583 input data for the Chemical Effect in the same manner as was described for the Quasi-static Stress Effect. The Chemical Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0      0      0
0.9870D+00 0.9966D+00 0.1002D+00 0.9997D+00 0.1000D+01
0.9977D+00 0.9950D+00 0.1001D+01 0.1001D+01 0.1005D+01
0.9991D+00 0.1000D+01 0.1003D+01 0.9945D+00 0.9952D+00
0.1000D+01 0.1001D+01.....etc.

```

8. Lines 584 to 728 input data for the Creep Effect in the same manner as was described for the Quasi-static Stress Effect. The Creep Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0      0      0
0.9072D+04 0.1034D+05 0.9792D+04 0.9696D+04 0.1080D+05
0.9936D+04 0.9959D+04 0.9544D+04 0.9733D+04 0.9450D+04
0.1016D+05 0.1067D+05 0.1054D+05 0.9723D+04 0.1018D+05
0.9827D+04 0.9758D+04.....etc.

```

9. Lines 729 to 873 input data for the Impact Effect in the same manner as was described for the Quasi-static Stress Effect. The Impact Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0      0      0
  0.5749D+01  0.7465D+01  0.6696D+01  0.6565D+01  0.8136D+01
  0.6894D+01  0.6926D+01  0.6362D+01  0.6615D+01  0.6237D+01
  0.7214D+01  0.7947D+01  0.7752D+01  0.6602D+01  0.7235D+01
  0.6744D+01  0.6649D+01.....etc.

```

10. Lines 874 to 1018 input data for the Thermal Fatigue Effect in the same manner as was described for the Quasi-static Stress Effect. The Thermal Fatigue Effect variable names have FORTRAN names given in Section 5.0, APPENDIX A.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0      0      0
  0.2464D+01  0.3199D+01  0.2870D+01  0.2813D+01  0.3487D+01
  0.2954D+01  0.2968D+01  0.2727D+01  0.2835D+01  0.2673D+01
  0.3092D+01  0.3406D+01  0.3322D+01  0.2830D+01  0.3101D+01
  0.2890D+01  0.2850D+01.....etc.

```

11a. Line 1019 specifies the source of the strength data by using flags. The flag names are AFDS, ADS and AODS. Setting a flag to 0 indicates actual experimental data is directly read from input. Setting a flag to 1 indicates simulated experimental data, normally distributed, is generated by the program via a random number generator. Setting a flag to 2 indicates simulated experimental data, lognormally distributed, is generated by the program via a random number generator. Setting a flag to 3 indicates data not available.

EXAMPLE:

```

1234567890
  0

```

11b. Lines 1020 to 1067 contain the actual experimental data for strength. The FORTRAN name for strength is STR.

EXAMPLE:

```

12345678901234567890123456789012345678901234567890
  0.1112D+02  0.8518D+01  0.7325D+01  0.7826D+01  0.7708D+01
  0.8277D+01  0.8921D+01  0.7464D+01  0.7464D+01  0.6842D+01
  0.7954D+01  0.7729D+01  0.7166D+01  0.9028D+01  0.8875D+01
  0.7711D+01  0.7478D+01.....etc.

```


12. The CORVC [1] parameters are IDO, LDX, IFRQ, IWT, MOPT, ICOPT, LDCOV, and LDINCD and are entered in that order as follows (line 1068):

EXAMPLE:

```
1234567890123456789012345678901234567890
      0  240    0    0    0    1   19   19
```

13. The RCOV [1] parameters are INTCEP, NOND, NDEP, LDCOV, LDB, LSR, and LDSCPE and are entered in that order as follows (line 1069):

EXAMPLE:

```
1234567890123456789012345678901234567890
      1    7    1   19   19   19    1
```

3.2.1 Discussion of Results

Execution of PROMISC (source code entitled PROMISC5.FOR) produces an output file that gives computed values for the empirical material constants, a_i . Output also includes statistics and diagnostics that enhance the PROMISC multiple linear regression analysis (see Section 2.0, Theoretical Background and/or Final Technical Report, Section 6 Increased Capability of PROMISC, NASA Grant No. NAG 3-867, Supp. 2, "Probabilistic Lifetime Strength of Aerospace Materials via Computational Simulation").

Execution of the PROMISC code for the example problem whose input is specified in Section 3.2 produces an output file that includes regression or least squares estimates of the exponents (empirical material constants, a_i) in the multifactor interaction equation under the heading BBBB. For example, the least squares estimate of the constant term (y -intercept, $\log S_0$) is predicted to be 4.99, quasi-static stress to be 0.14, mechanical fatigue to be -0.05, and so on.

To see "how well" the data fit the regression equation, consider the subheading which contains R-squared. From the R-squared coefficients, it can be observed that about 99.99% of the variation in the data can be explained by the regression equation. Recall that 100% is the value when the model is exact. Under the next subheading, the ANOVA Table helps to quantify the model adequacy in terms of probability. Under the source "regression" it is observed that the p-value is virtually zero. The asterisks in the "Overall F" column indicate the F-statistic exceeded 99,999.99 and therefore could not be displayed in the space allocated.

Among the seven factors (effects or primitive variables) in the multifactor interaction equation, we can associate relative importance with the size of the p-values in the "Sequential Statistics" Table. The smaller the p-value (i.e., "Prob. of Larger F") then the more significance associated with the factor. Notice that factors 1, 2 and 5 are significant with p-values below the 0.05 level. However factors 3, 4, 6 and 7 are insignificant. Therefore, it may be beneficial to reanalyze the data by deleting factors 3, 4, 6 and 7.

To look for outlying observations, the "Case Analysis" Table is used. The column headed by "Cook's D" is used for the detection of aberrant observations. The output is complicated in this case by the number of observations present in the data set. As explained in Section 3.1.1, the larger values of "Cook's D" indicate observations which are further away from the center of the data. However, when 240 observations are present the process of scanning the values of Cook's D is more tedious. Observation 85 is the one with the largest Cook's D of 0.0592 and standardized residual of 2.6871, both of which are within acceptable limits.

The residuals and standardized residuals can be used to test the assumptions of normality for the errors.

3.3 General PROMISC Program Notes

1. Any effect data, $\left[\frac{A_F - A}{A_F - A_0} \right]$, not included in the model is set to zero.
2. Fatigue cycles should be input as log cycles rather than as cycles. Reasons are the same as for PROMISS.
3. Strength response, S, should be input as strength in MPa or ksi. PROMISC will internally calculate log S.
4. The stress data effect in PROMISC has not been customized for negative lognormal values as it has been for PROMISS.

4.0 REFERENCES

1. IMSL, "STAT/LIBRARY, FORTRAN Subroutines for Statistical Analysis", Houston, Texas.
2. SAS Institute, Inc., SAS/GRAPH User's Guide, Version 5 Edition, Cary, NC: SAS Institute, Inc., 1985, p. 596.
3. Chamis, C.C., "Simplified Composite Micromechanics Equations for Strength, Fracture Toughness, Impact Resistance and Environmental Effects," NASA TM 83696, Jan., 1984.
4. Hopkins, D.A., "Nonlinear Analysis for High-Temperature Multilayered Fiber Composite Structures," NASA TM 83754, Aug., 1984.
5. Chamis, C.C. and Hopkins, D., "Thermoviscoplastic Nonlinear Constitutive Relationships for Structural Analysis of High Temperature Metal Matrix Composites," NASA TM 87291, Nov., 1985.
6. Hopkins, D. and Chamis, C.C., "A Unique Set of Micromechanics Equations for High Temperature Metal Matrix Composites," NASA TM 87154.
7. Ross, S.M., Introduction to Probability and Statistics for Engineers and Scientists, Wiley, N.Y., 1987, p.278.
8. Siddall, J.N., "A Comparison of Several Methods of Probabilistic Modeling," Proceedings of the Computers in Engineering Conference, ASME San Diego, CA, Vol. 4, 1982, pp. 231-238.
9. Scott, D.W., "Nonparametric Probability Density Estimation by Optimization Theoretic Techniques," NASA CR-147763, April, 1976.

5.0 APPENDIX A

PRIMITIVE VARIABLES, SYMBOLS, AND UNITS

Table A1.2 Primitive variables, symbols, and units for PROMISS

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	SI	Units U.S.
<u>QUASI-STATIC STRESS EFFECT</u>				
Ultimate value	S _{SF}	AF	MPa	ksi
Current value	σ_S	A	MPa	ksi
Reference value	σ_{SO}	AO	MPa	ksi
<u>IMPACT EFFECT</u>				
Ultimate value	S _{DF}	AF2	Dimensionless	
Current value	σ_D	A2	Dimensionless	
Reference value	σ_{DO}	AO2	Dimensionless	
<u>OTHER MECHANICAL EFFECTS</u>				
Ultimate value	A _{3F}	AF3	Dimensionless	
Current value	A ₃	A3	Dimensionless	
Reference value	A _{3O}	AO3	Dimensionless	
<u>TEMPERATURE</u>				
Ultimate value	T _F	AF4	°C	°F
Current value	T	A4	°C	°F
Reference value	T _O	AO4	°C	°F
<u>THERMAL SHOCK</u>				
Ultimate value	A _{5F}	AF5	Dimensionless	
Current value	A ₅	A5	Dimensionless	
Reference value	A _{5O}	AO5	Dimensionless	

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	Units	
			SI	U.S.
<u>OTHER THERMAL EFFECTS</u>				
Ultimate value	A _{6F}	AF6	Dimensionless	
Current value	A ₆	A6	Dimensionless	
Reference value	A ₆₀	AO6	Dimensionless	
<u>CHEMICAL REACTION</u>				
Ultimate value	R _F	AF7	Dimensionless	
Current value	R	A7	Dimensionless	
Reference value	R ₀	AO7	Dimensionless	
<u>RADIATION</u>				
Ultimate value	A _{8F}	AF8	Dimensionless	
Current value	A ₈	A8	Dimensionless	
Reference value	A ₈₀	AO8	Dimensionless	
<u>OTHER EFFECTS</u>				
Ultimate value	A _{9F}	AF9	Dimensionless	
Current value	A ₉	A9	Dimensionless	
Reference value	A ₉₀	AO9	Dimensionless	
<u>CREEP</u>				
Ultimate value	t _{CF}	AF10	Hours	Hours
Current value	t _C	A10	Hours	Hours
Reference value	t _{CO}	AO10	Hours	Hours
<u>MECHANICAL FATIGUE</u>				
Ultimate value	N _{MF}	AF11	log of cycles	
Current value	N _M	A11	log of cycles	
Reference value	N _{MO}	AO11	log of cycles	

Primitive Variables (Effect)	Theory Symbol	FORTTRAN Name	Units SI	U.S.
<u>OTHER TIME DEPENDENT MECHANICAL EFFECT</u>				
Ultimate value	A _{12F}	AF12	Dimensionless	
Current value	A ₁₂	A12	Dimensionless	
Reference value	A _{12O}	AO12	Dimensionless	
<u>THERMAL AGING</u>				
Ultimate value	A _{13F}	AF13	Dimensionless	
Current value	A ₁₃	A13	Dimensionless	
Reference value	A _{13O}	AO13	Dimensionless	
<u>THERMAL FATIGUE</u>				
Ultimate value	N _{TF}	AF14	log of cycles	
Current value	N _T	A14	log of cycles	
Reference value	N _{TO}	AO14	log of cycles	
<u>OTHER TIME- DEPENDENT THERMAL EFFECTS</u>				
Ultimate value	A _{15F}	AF15	Dimensionless	
Current value	A ₁₅	A15	Dimensionless	
Reference value	A _{15O}	AO15	Dimensionless	
<u>CORROSION</u>				
Ultimate value	A _{16F}	AF16	Dimensionless	
Current value	A ₁₆	A16	Dimensionless	
Reference value	A _{16O}	AO16	Dimensionless	
<u>SEASONAL ATTACK</u>				
Ultimate value	A _{17F}	AF17	Dimensionless	
Current value	A ₁₇	A17	Dimensionless	
Reference value	A _{17O}	AO17	Dimensionless	

Primitive Variables (Effect)	Theory Symbol	FORTRAN Name	SI	Units	U.S.
<u>OTHER TIME-DEPENDENT EFFECT</u>					
Ultimate value	A _{18F}	AF18		Dimensionless	
Current value	A ₁₈	A18		Dimensionless	
Reference value	A _{18O}	AO18		Dimensionless	

6.0 APPENDIX B

PROMISC SAMPLE PROBLEM: INPUT AND OUTPUT FILES

Sample problems are discussed in sections 3.1 and 3.2. One sample problem corresponds to each section. The input and output file names for each sample problem are listed below. The enclosed disk also includes the same files.

3.1 PROMISC Input For Fixed Model With Actual Experimental Data (40 Data Points)

Input File(s): 31PRC4.INP
Output File: 31PRC4.OUT

3.2 PROMISC Input For Fixed Model With Actual Experimental Data (240 Data Points)

Input File(s): 32PRC5.INP
Output File: 32PRC5.OUT

7.0 APPENDIX C

IMSL SUBROUTINE CALLS FROM PROMISC

1. RNSET - Initializes a random seed for use in the IMSL random number generators.
2. RNNOR - Generates pseudorandom numbers from a standard normal distribution using an inverse CDF method.
3. RNLNL - Generates pseudorandom numbers from a lognormal distribution.
4. CORVC - Generates sums of squares and crossproducts.
5. RCOV - Performs the multiple linear regression.
6. RSTAT - Computes statistics related to the regression.
7. RCASE - Computes further statistics and diagnostics related to the regression.
8. Other IMSL Subroutines - SSCAL, SADD, UMACH, WRRRN, and WRIRN.

12.0 APPENDIX 3: PROMISS SENSITIVITY STUDY PLOTS

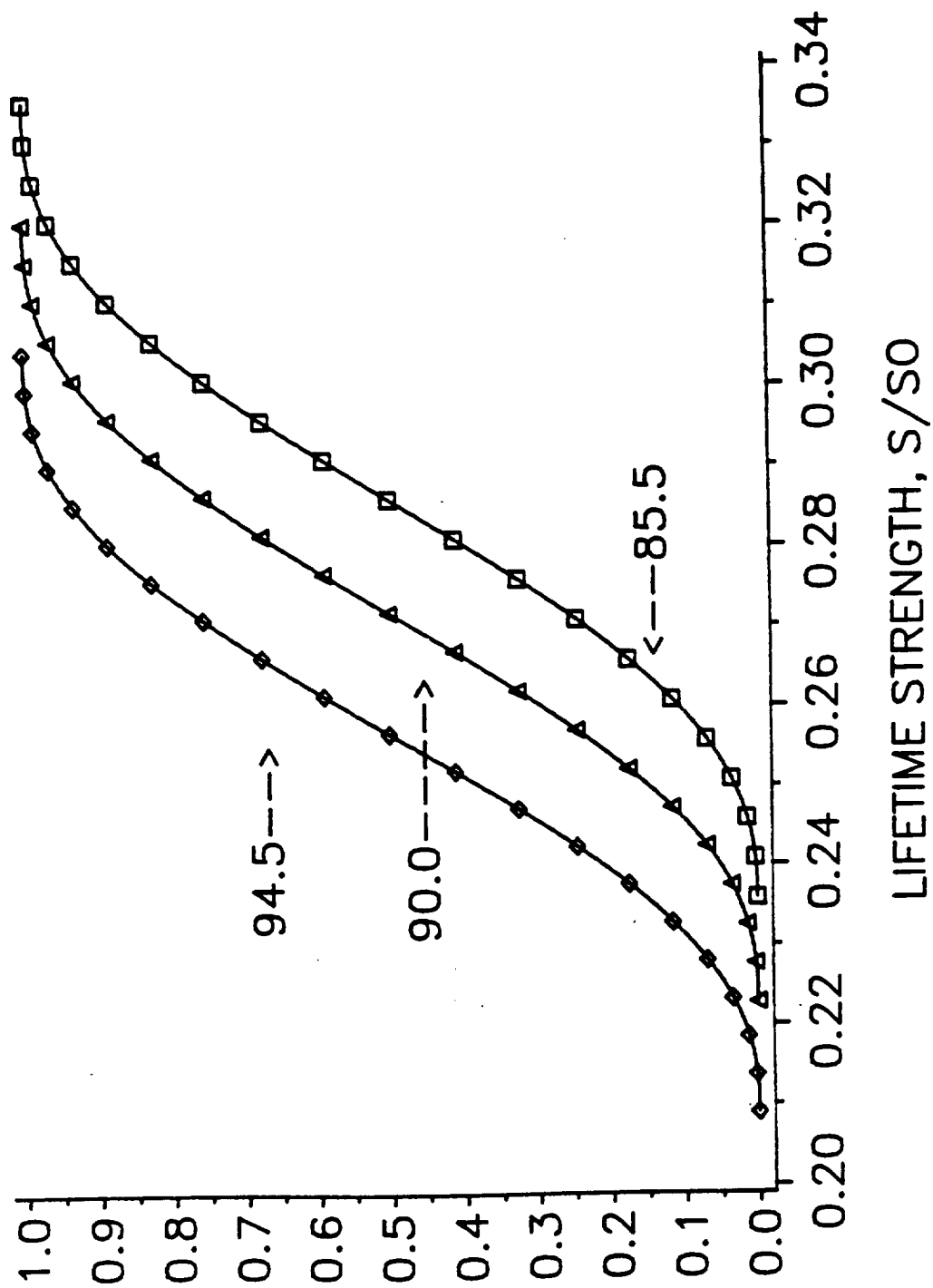


Figure A.1 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF STRESS ON (ksi) PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT ROOM TEMPERATURE

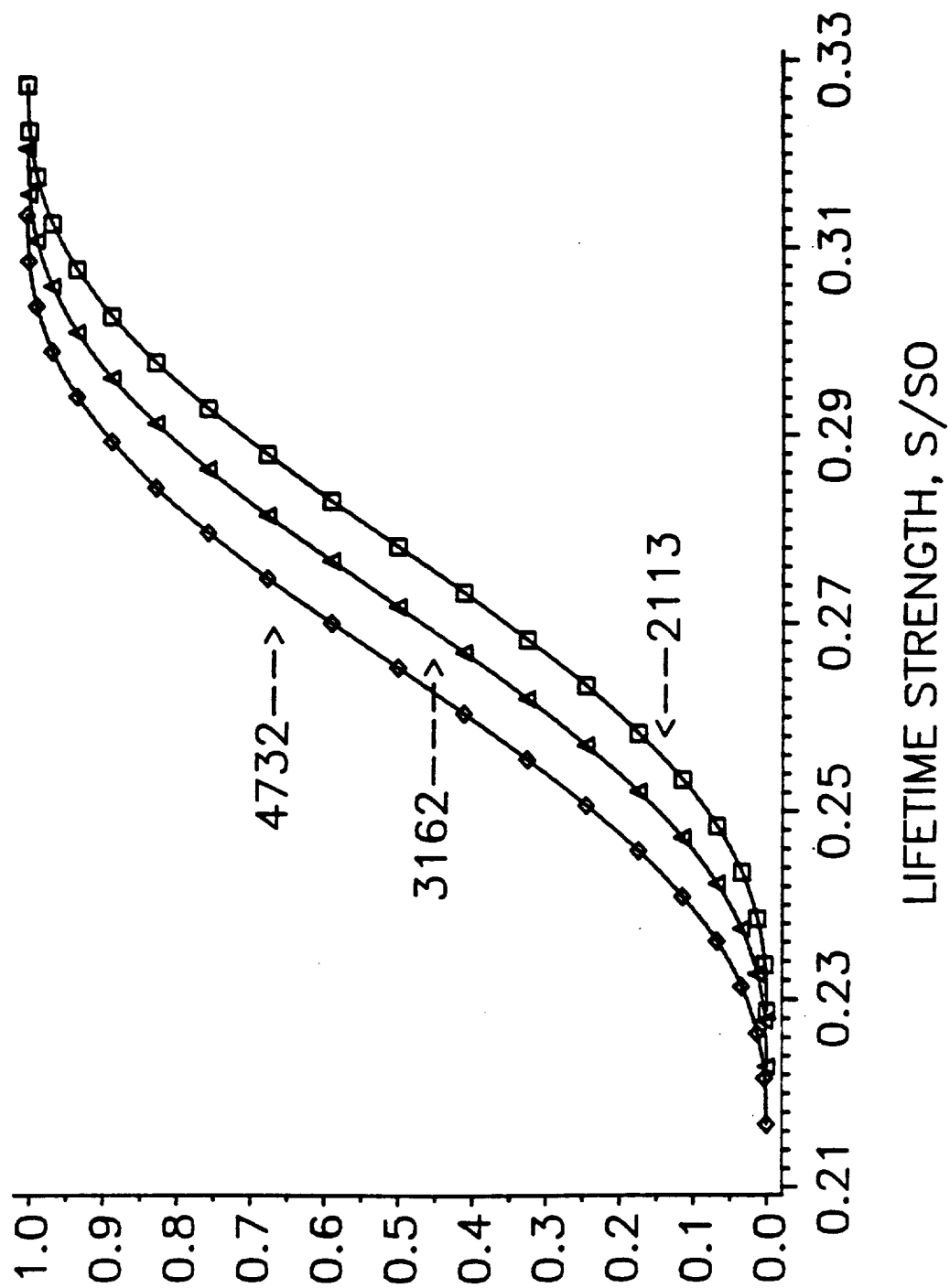


Figure A.2 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF MECHANICAL FATIGUE (CYCLES) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT ROOM TEMPERATURE

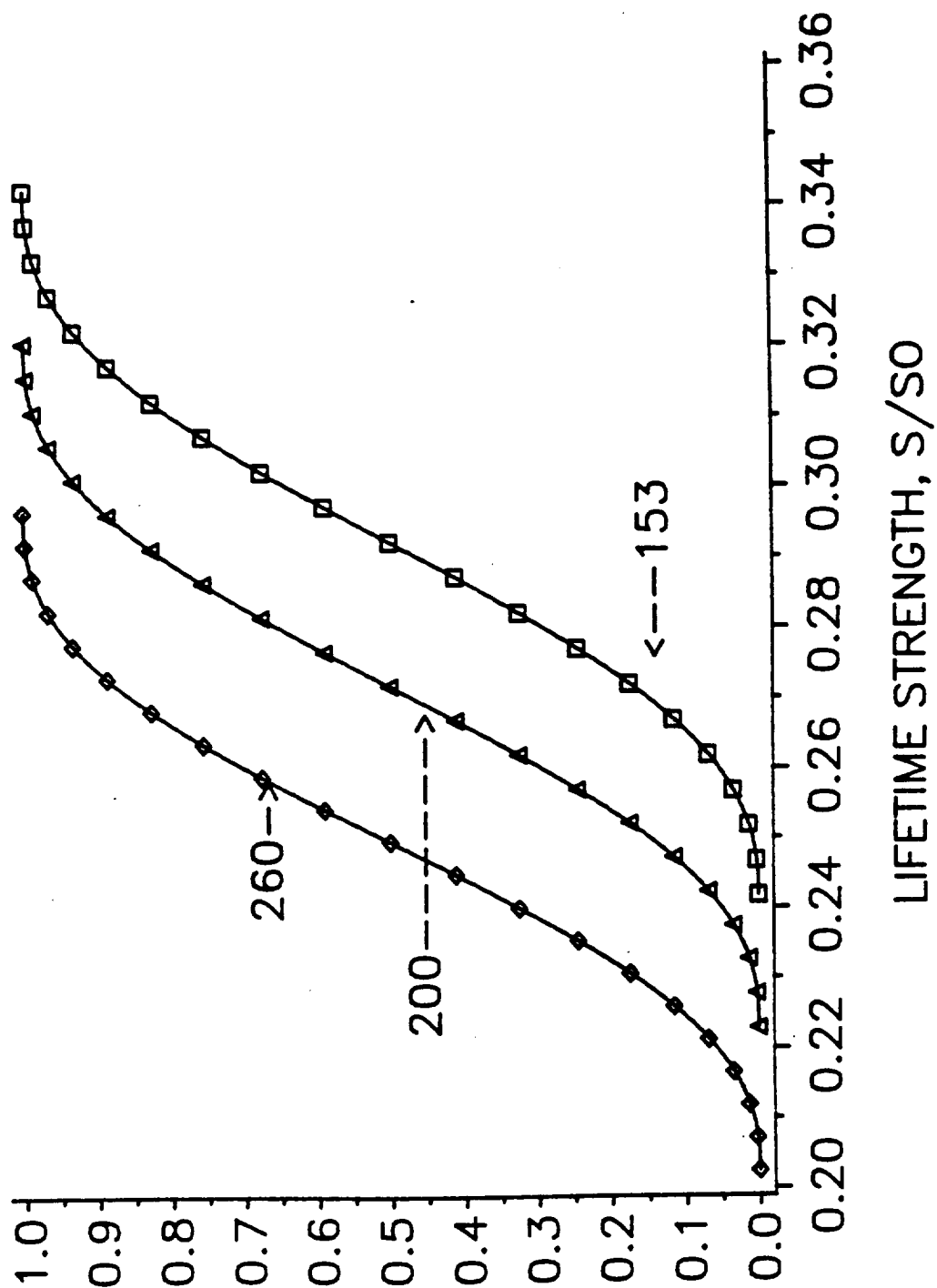


Figure A.3 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF THERMAL FATIGUE (CYCLES) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT ROOM TEMPERATURE

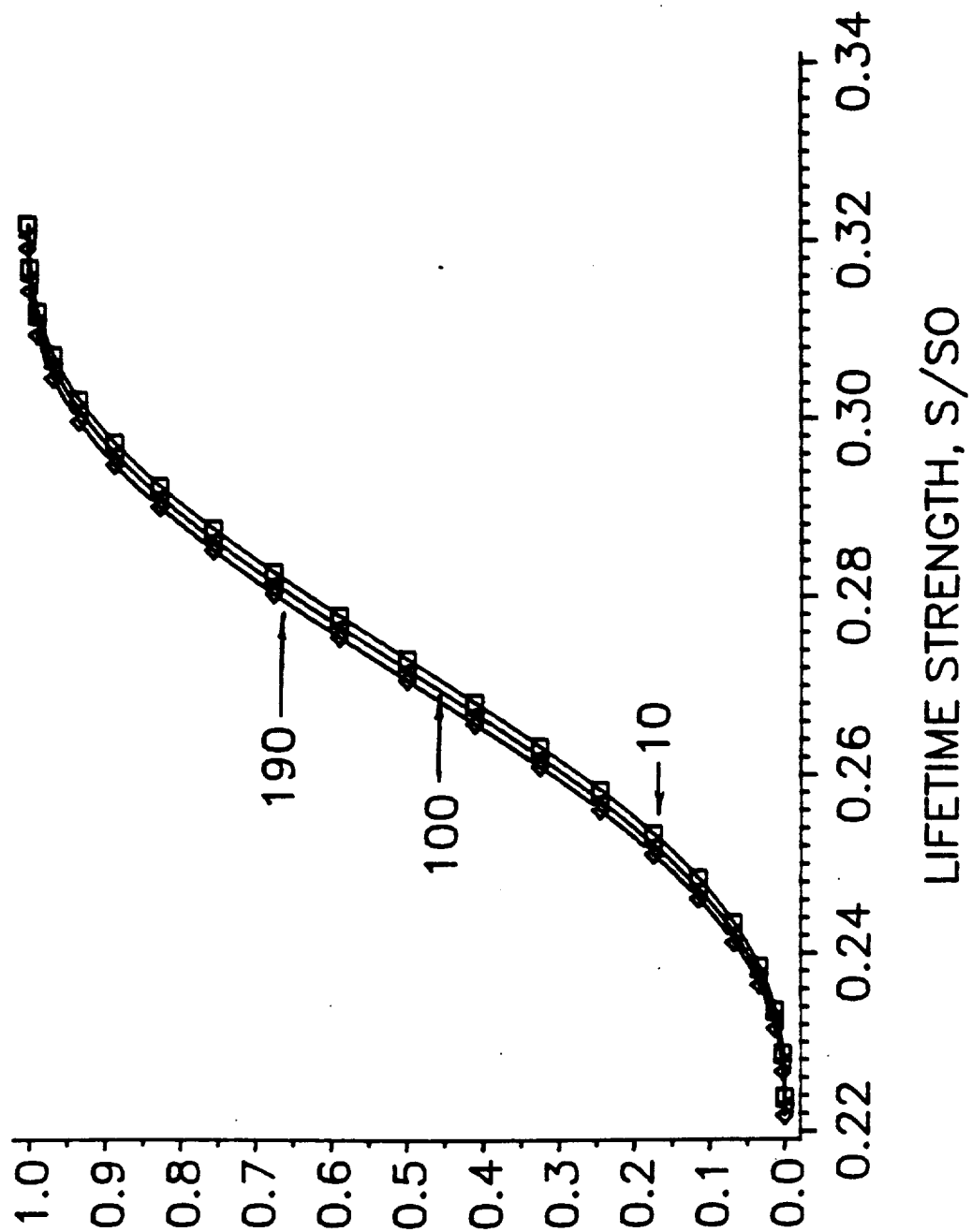


Figure A.4 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF CREEP (HOURS) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT ROOM TEMPERATURE

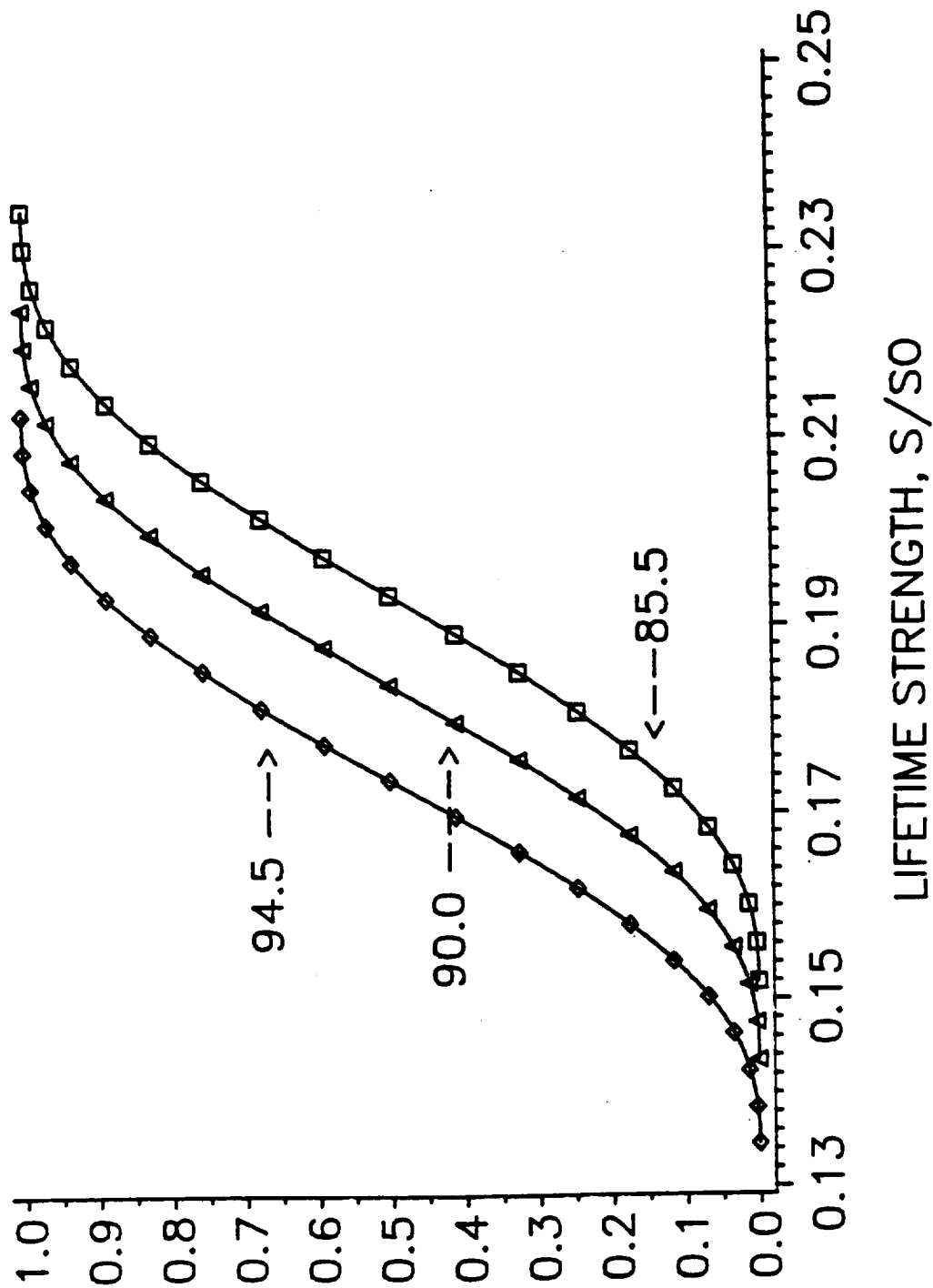


Figure A.5 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF STRESS (ksi) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT 0.57 Tm

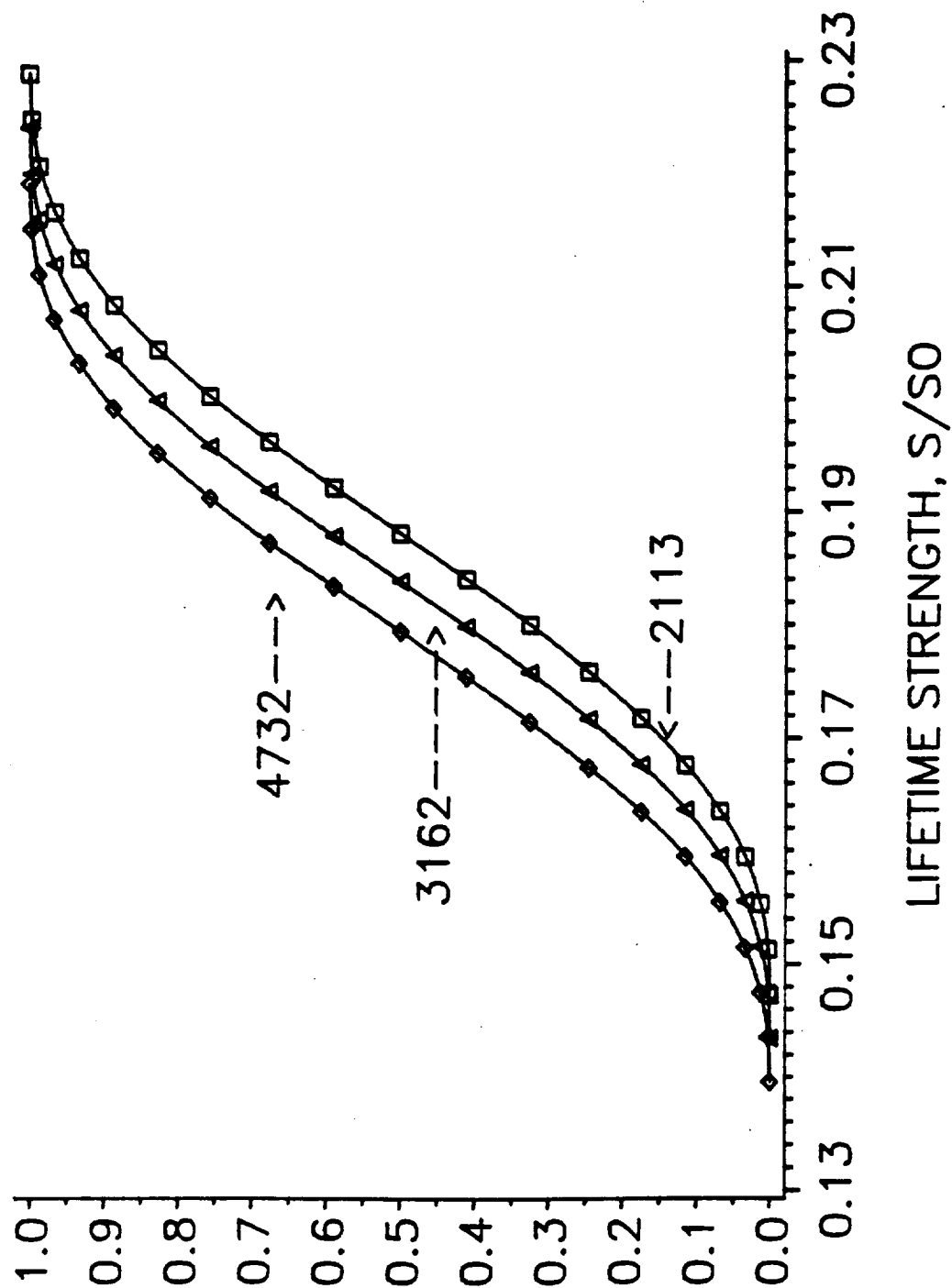


Figure A.6 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF MECHANICAL FATIGUE (CYCLES) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT 0.57 T_m

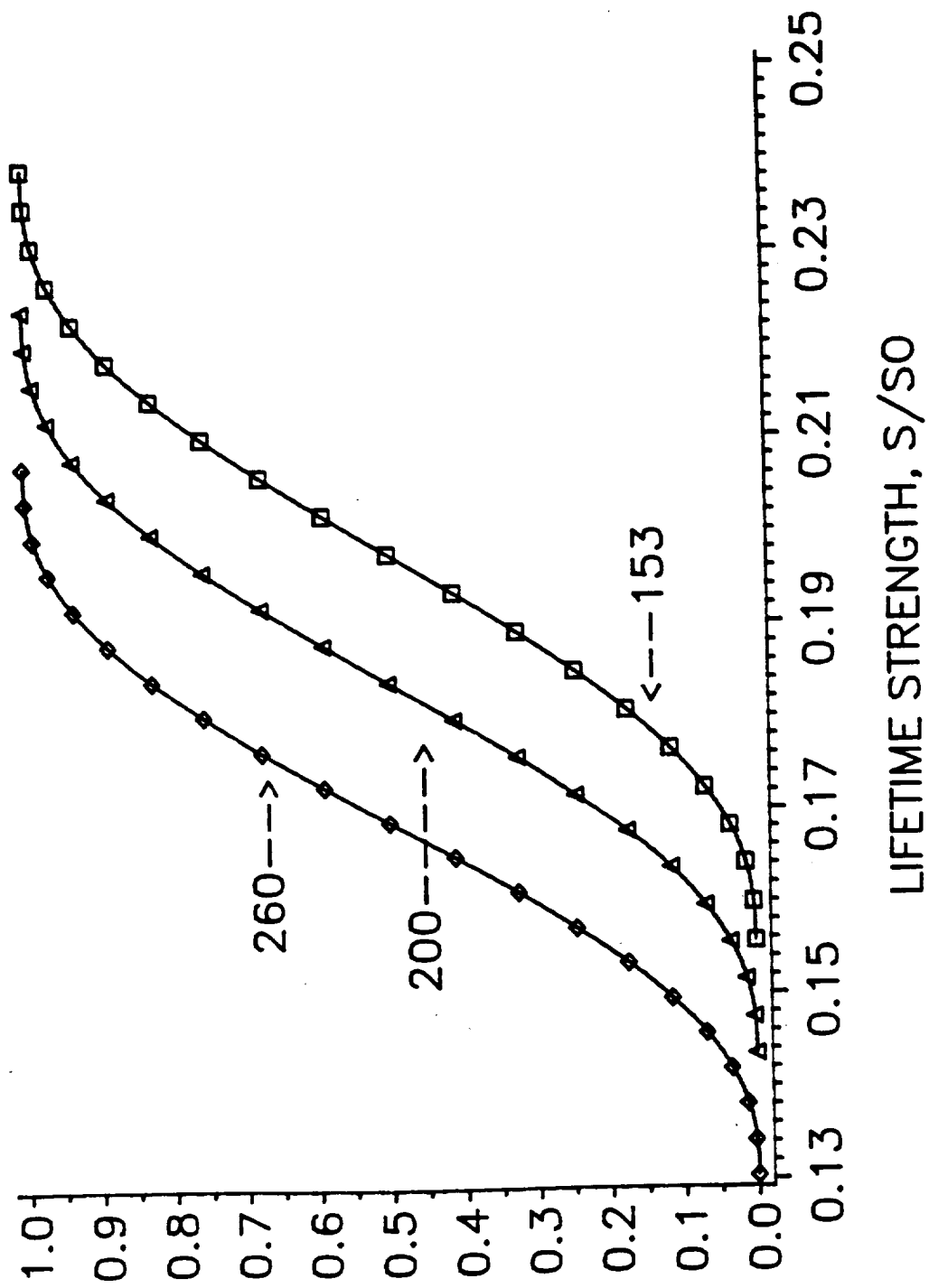


Figure A.7 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF THERMAL FATIGUE (CYCLES) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT T_m

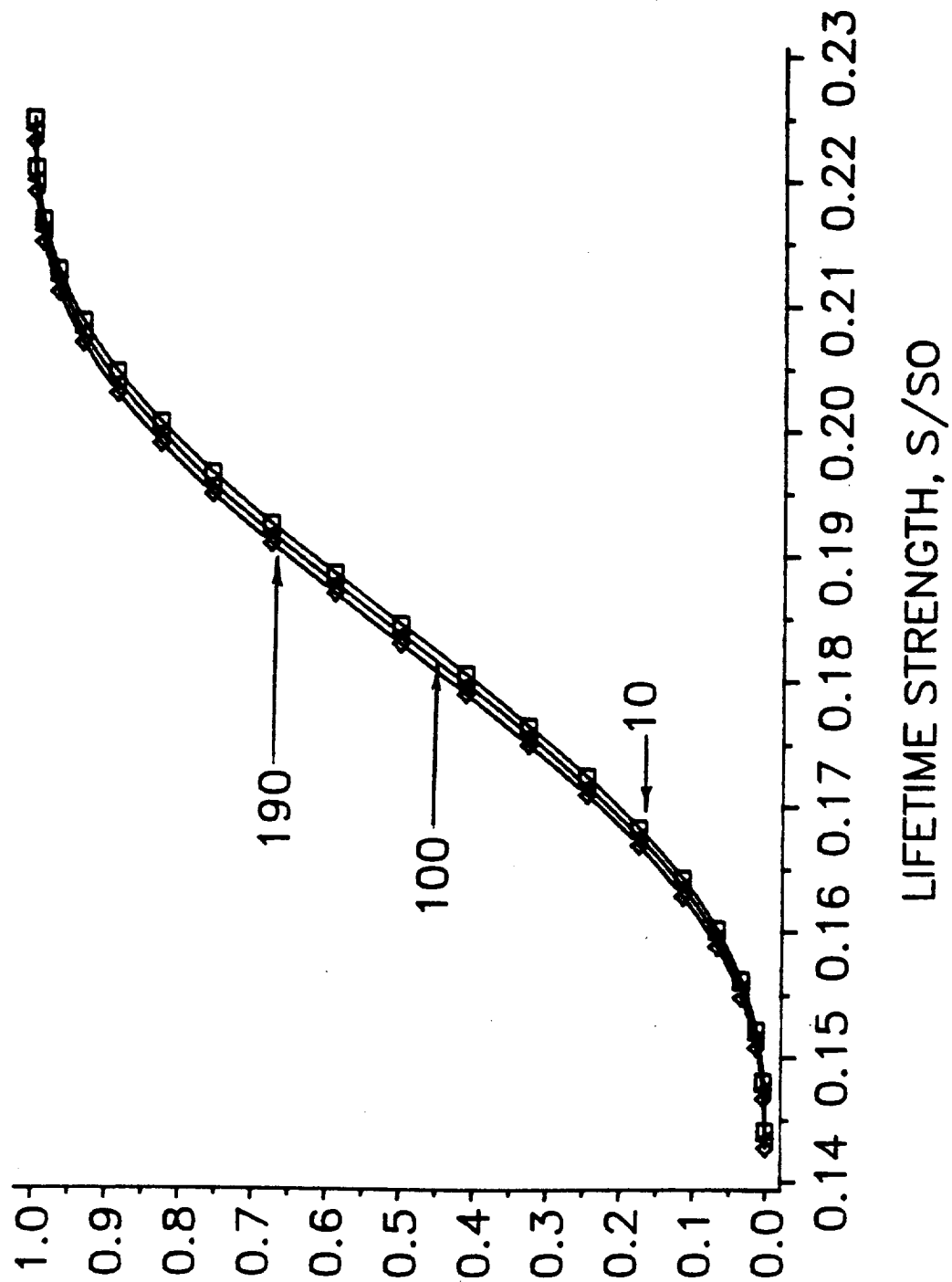


Figure A.8 COMPARISON OF VARIOUS LEVELS OF UNCERTAINTY OF CREEP (HOURS) ON PROBABLE STRENGTH FOR A NICKEL-BASED SUPERALLOY AT 0.57 T_m

13.0 APPENDIX 4 : MATERIAL DATA PLOTS

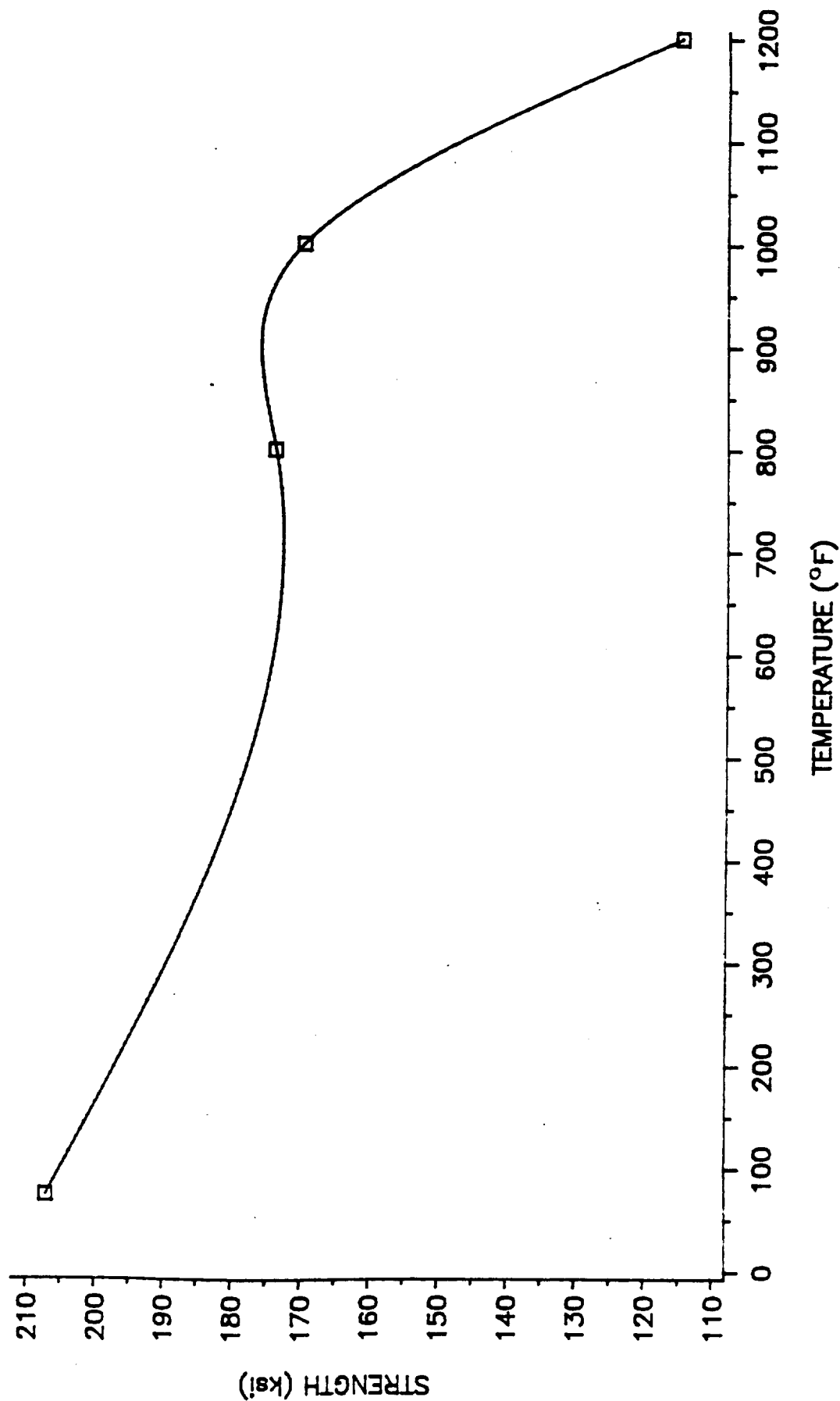
13.1 Introduction

This appendix displays plots of material properties data collected from the open literature for certain aerospace materials. Included are tensile (quasi-static stress), fatigue and creep plots for INCONEL 718, tensile and fatigue plots for other nickel-base superalloys and creep data for metal matrix composites and reinforcement fibers.

13.2 Tensile, Fatigue and Creep Data Plots of INCONEL 718

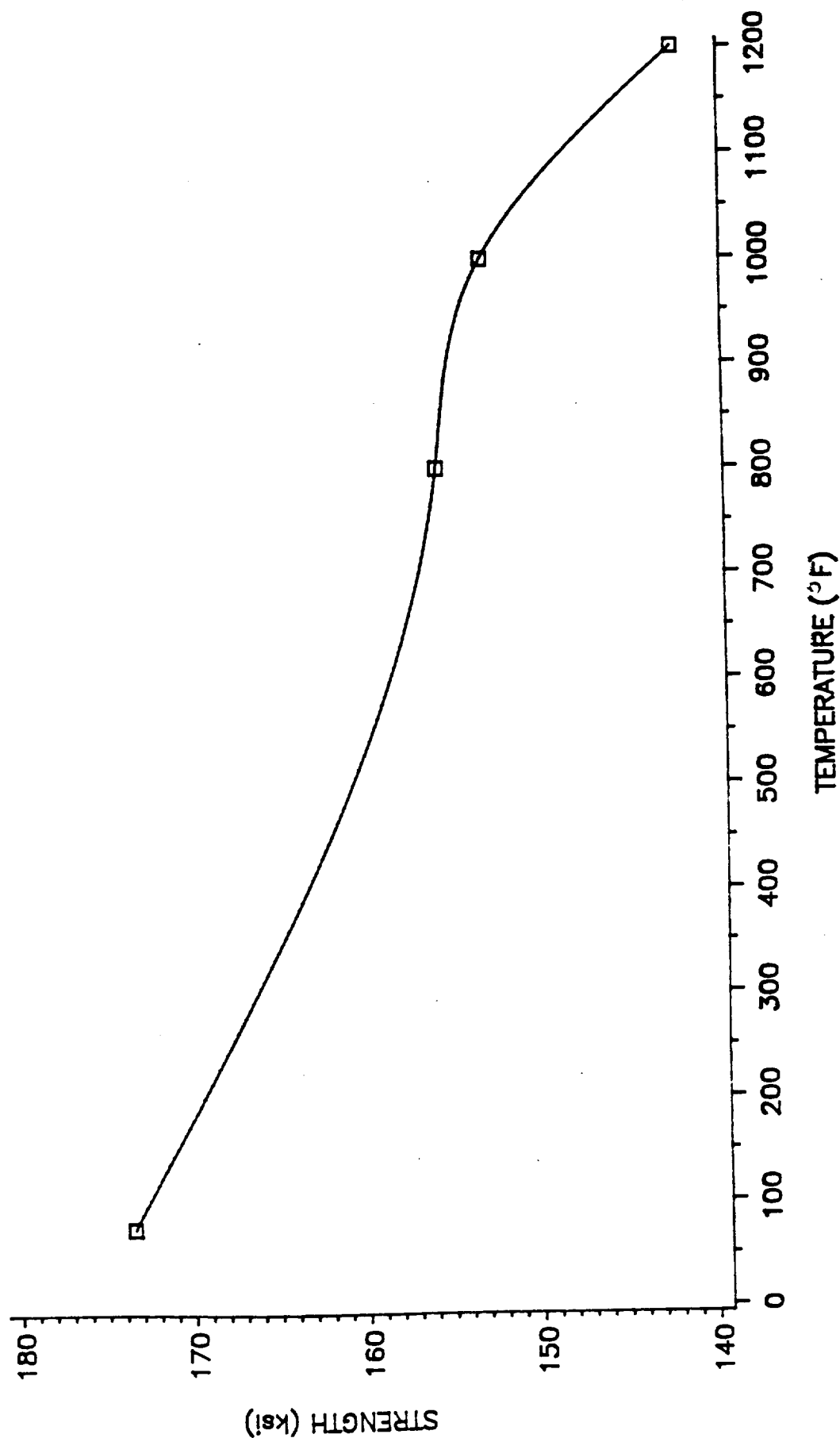
.025" THICK SHEET
COLD WKD 20% & AGED

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



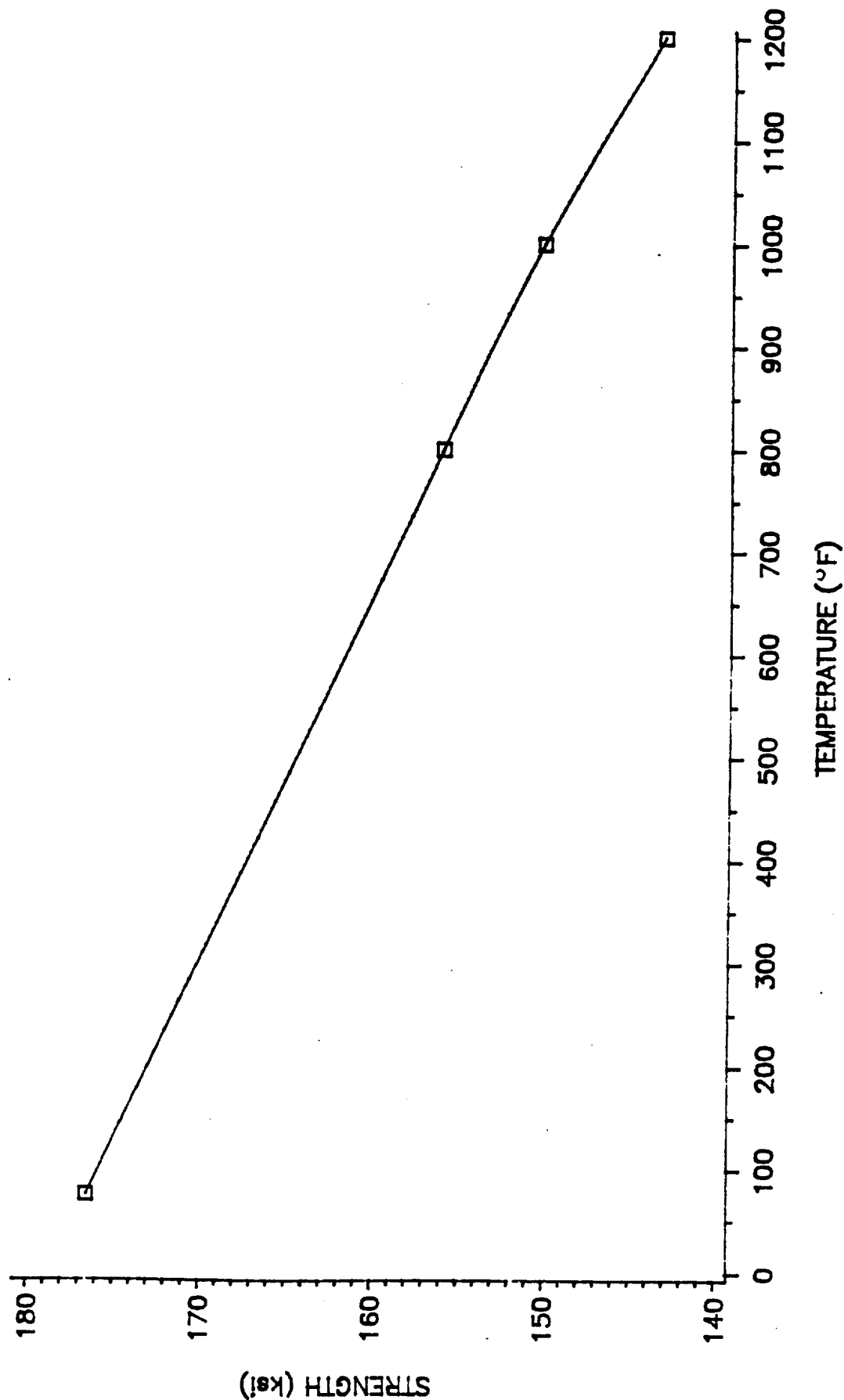
.025" THICK SHEET
SMOOTH SPECIMEN
ANND AT 1750 F & AGED

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



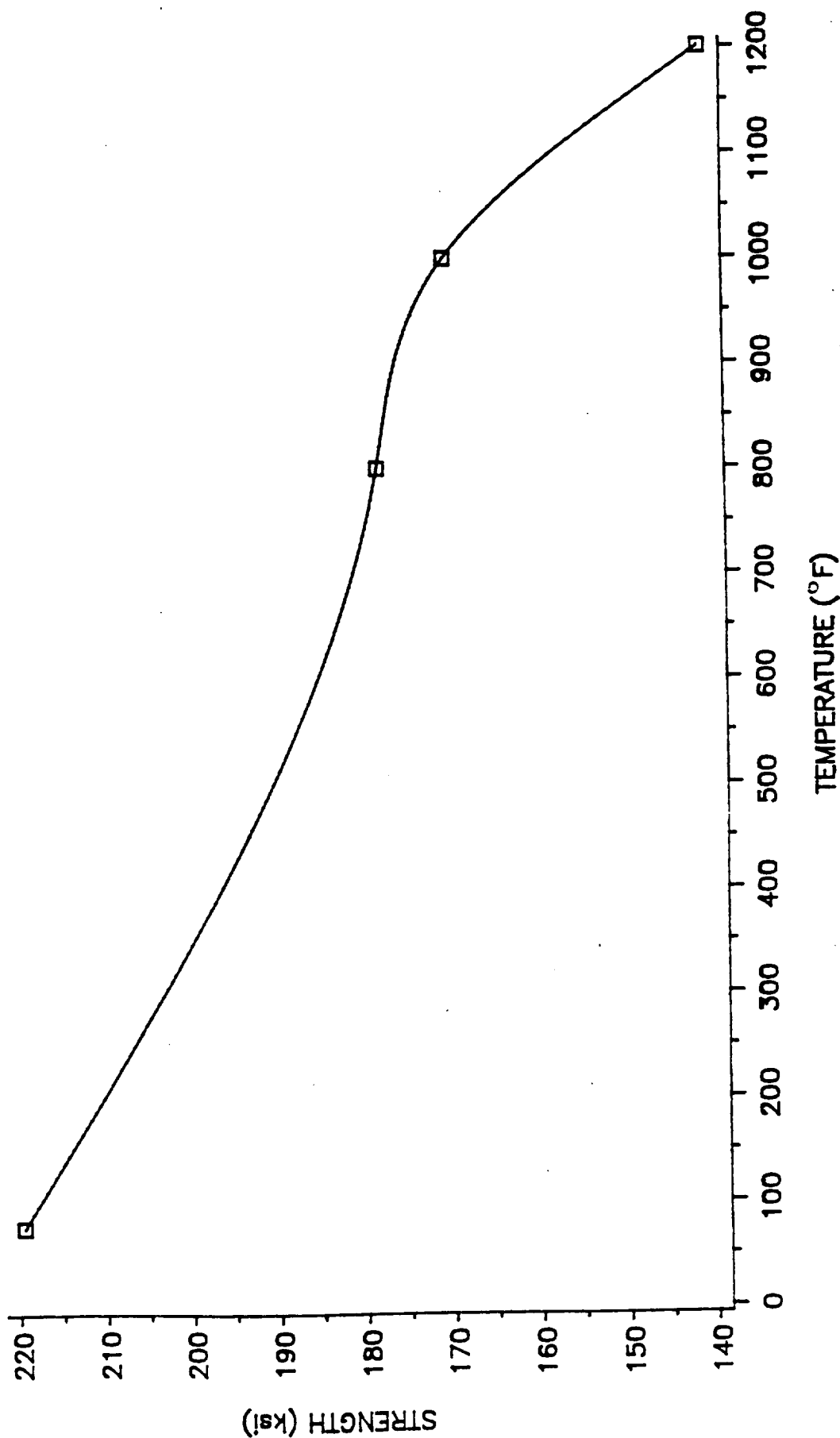
.025" THICK SHEET
SMOOTH SPECIMEN
ANNELED AT 1950 F & AGED

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



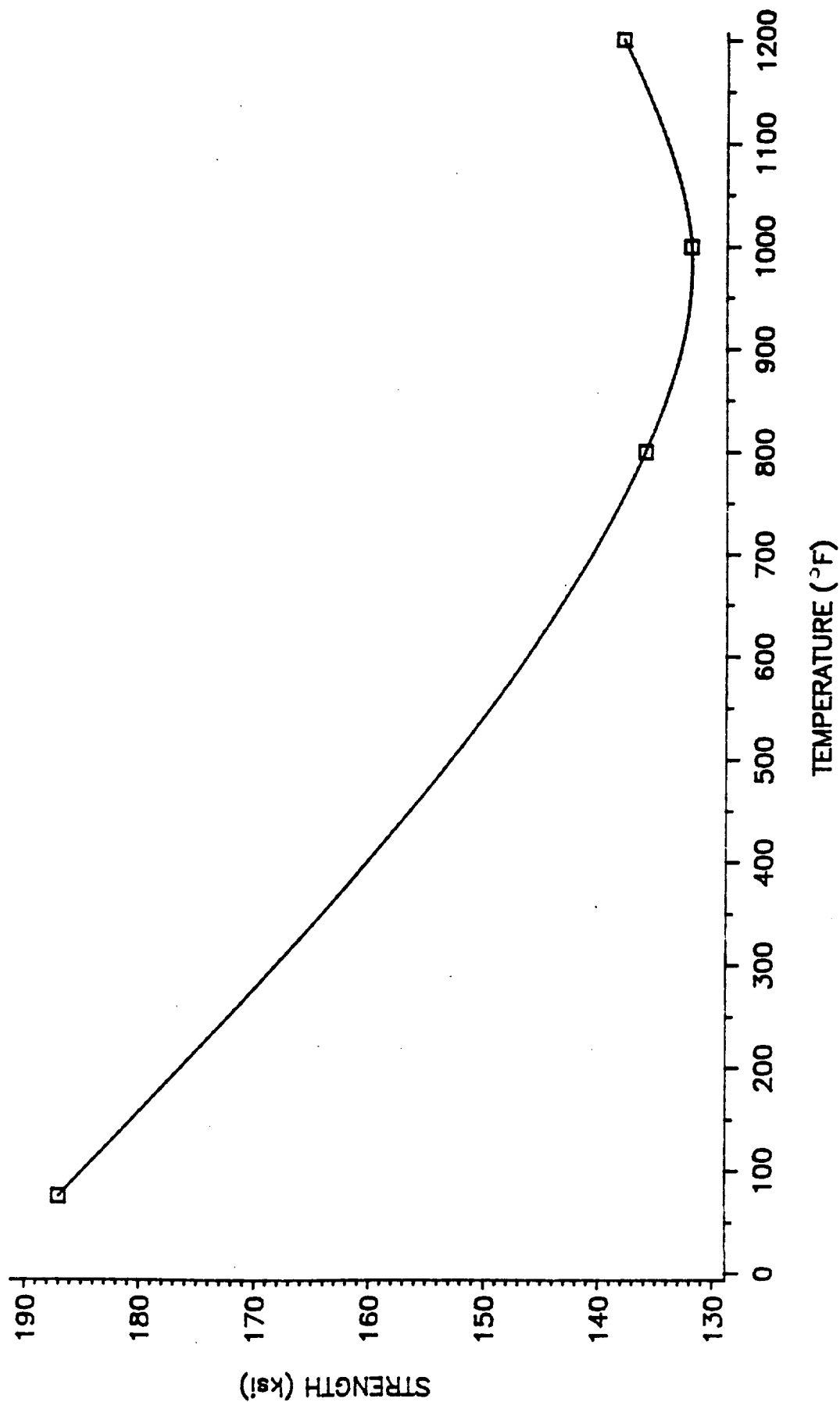
.025" THICK SHEET
NOTCHED Kt > 20
COLD WKD 20% & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



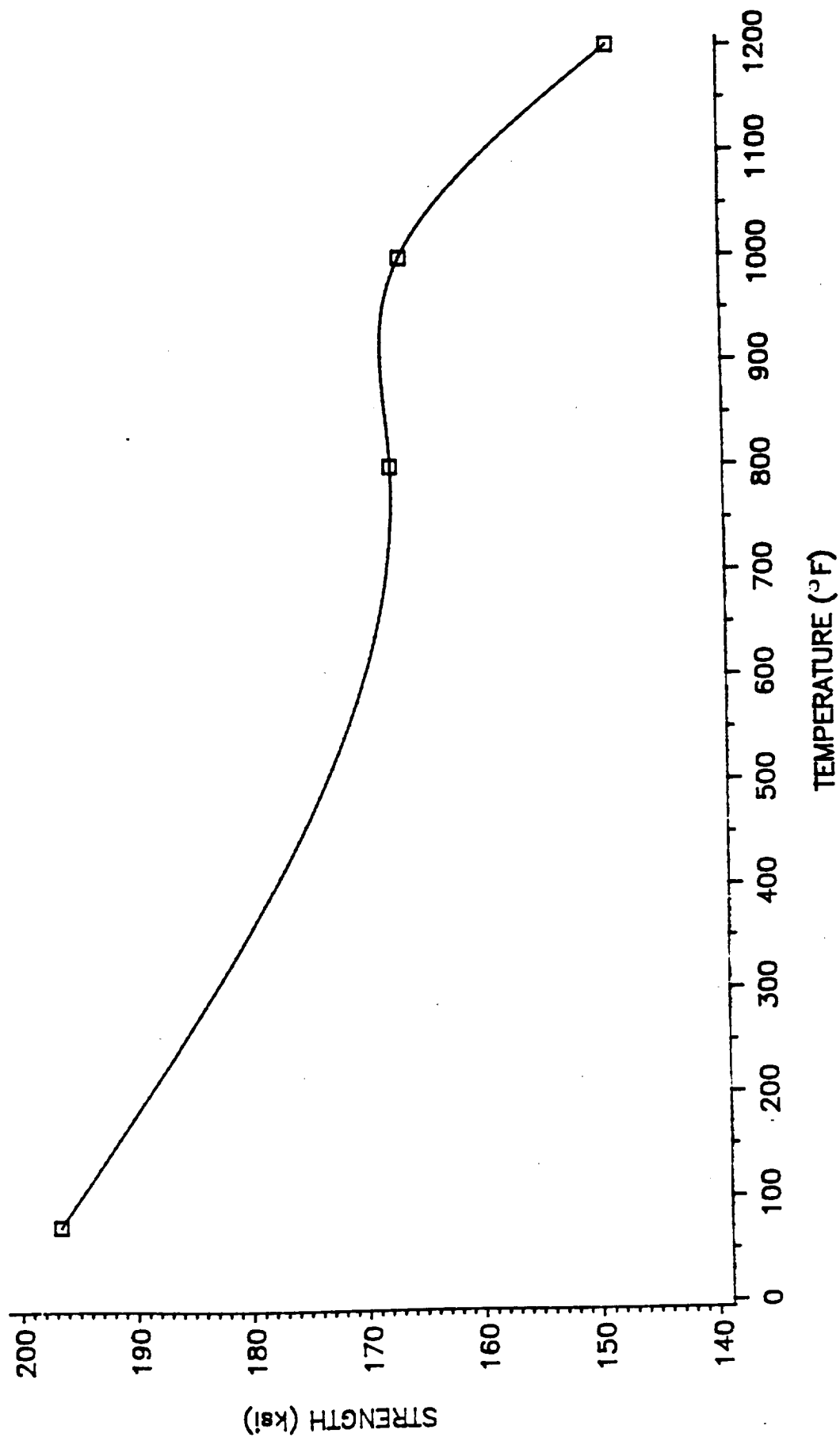
.025" THICK SHEET
NOTCHED Kt > 20
ANNULED AT 1750 F & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



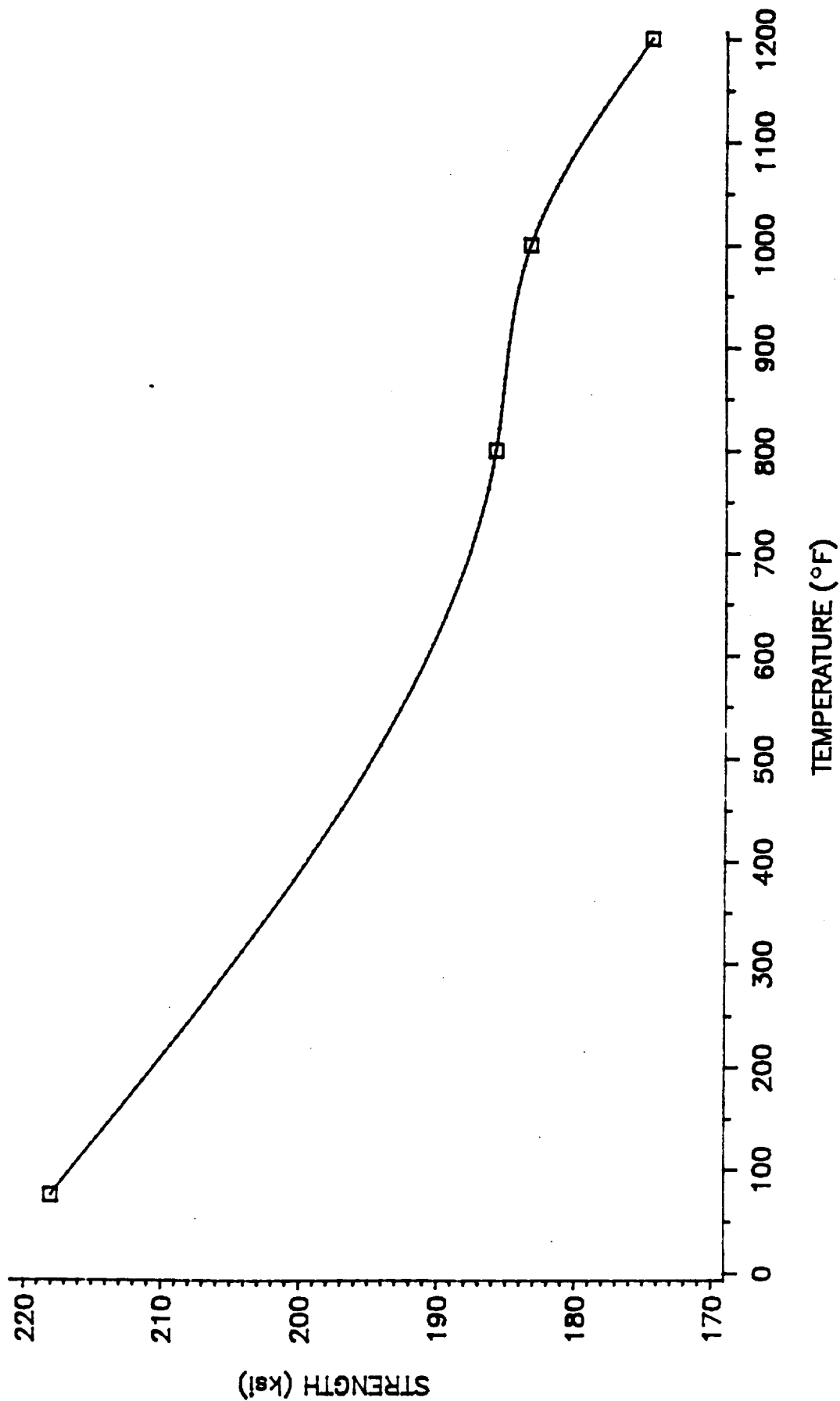
.025" THICK SHEET
NOTCHED Kt > 20
ANNILD AT 1950 F & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



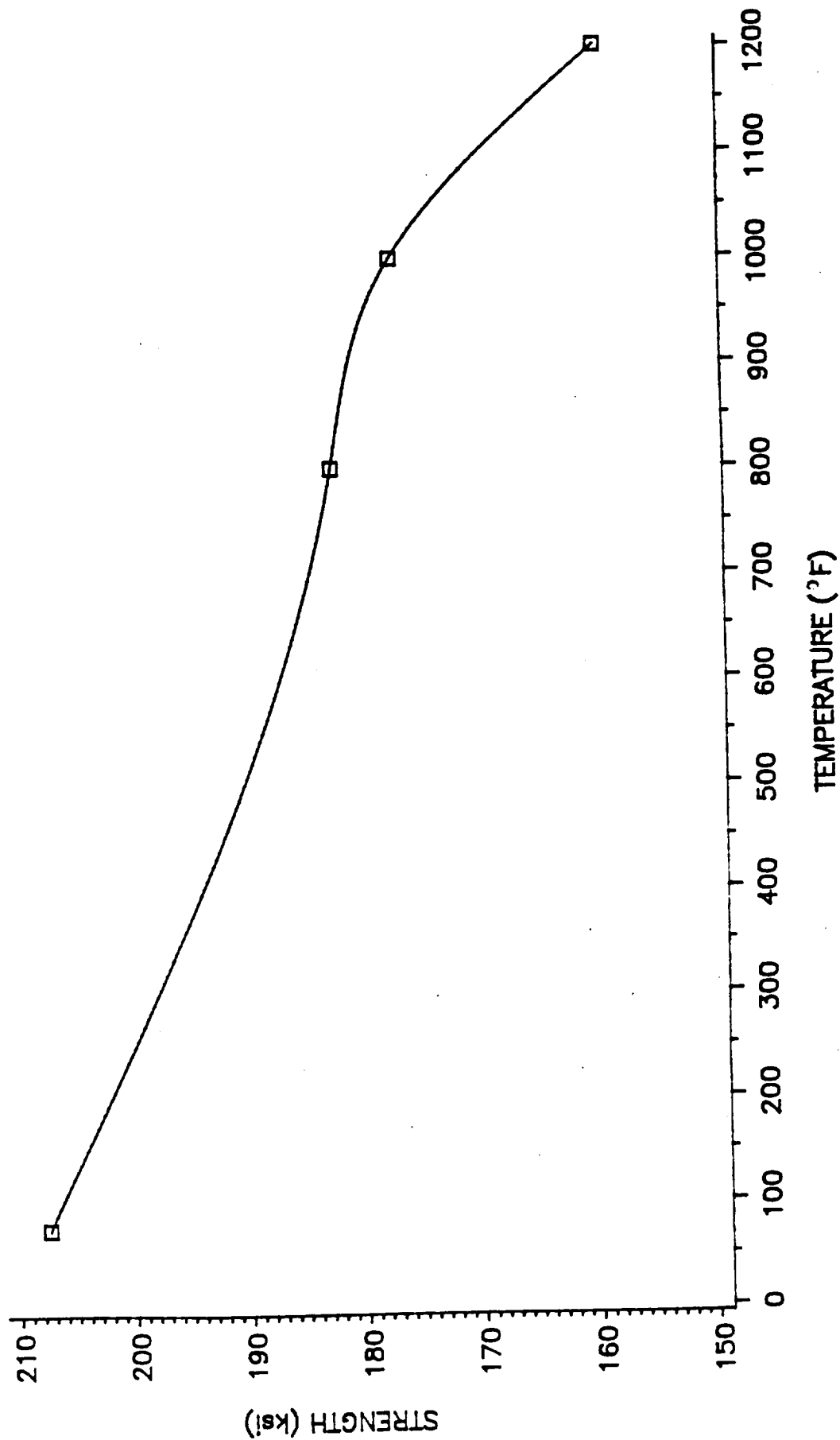
.025" THICK SHEET
COLD WKD 20% & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



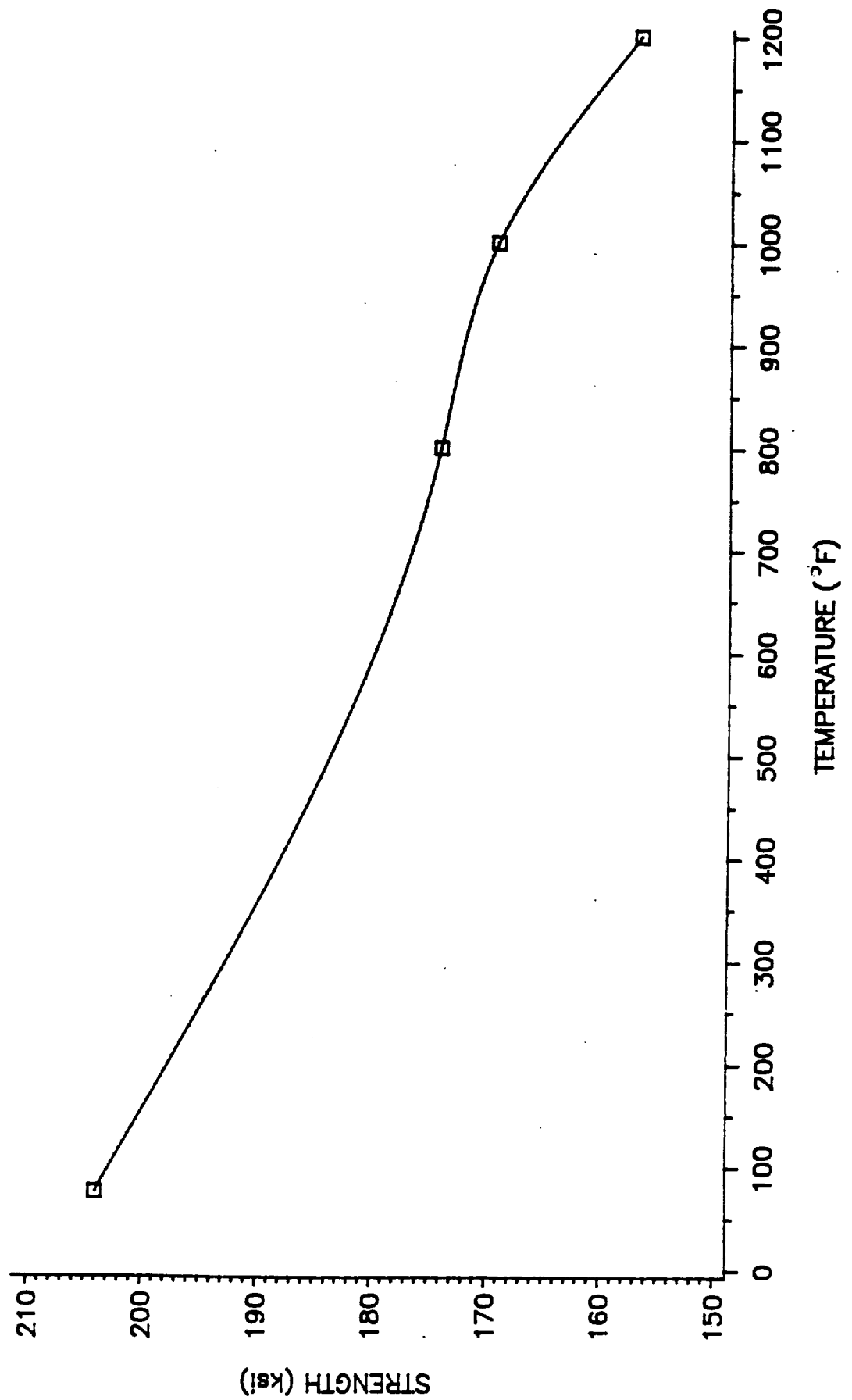
.025" THICK SHEET
SMOOTH SPECIMEN
ANNLD AT 1750 F & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



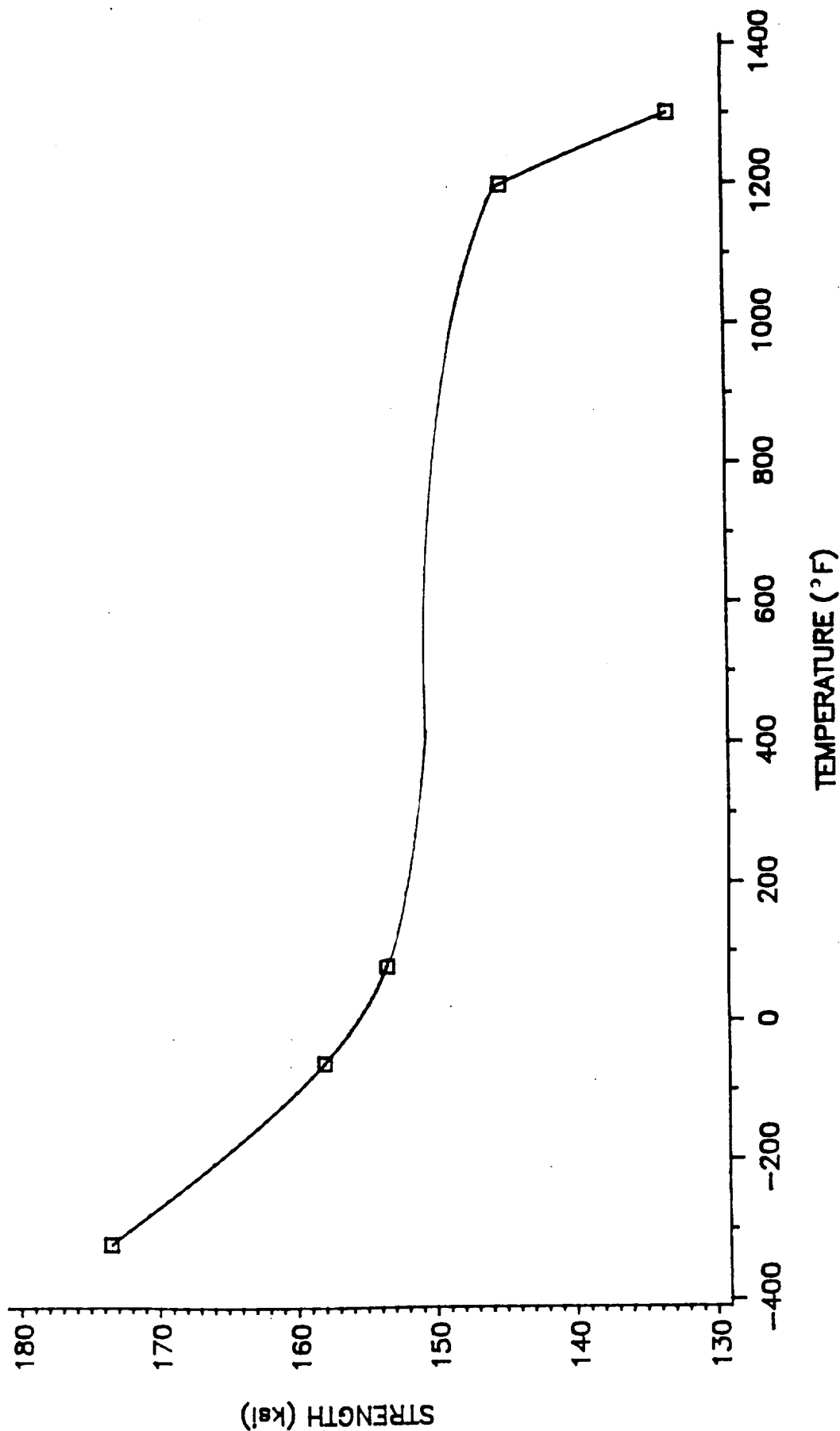
.025" THICK SHEET
SMOOTH SPECIMEN
ANNLD AT 1950 F & AGED

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR INCONEL 718



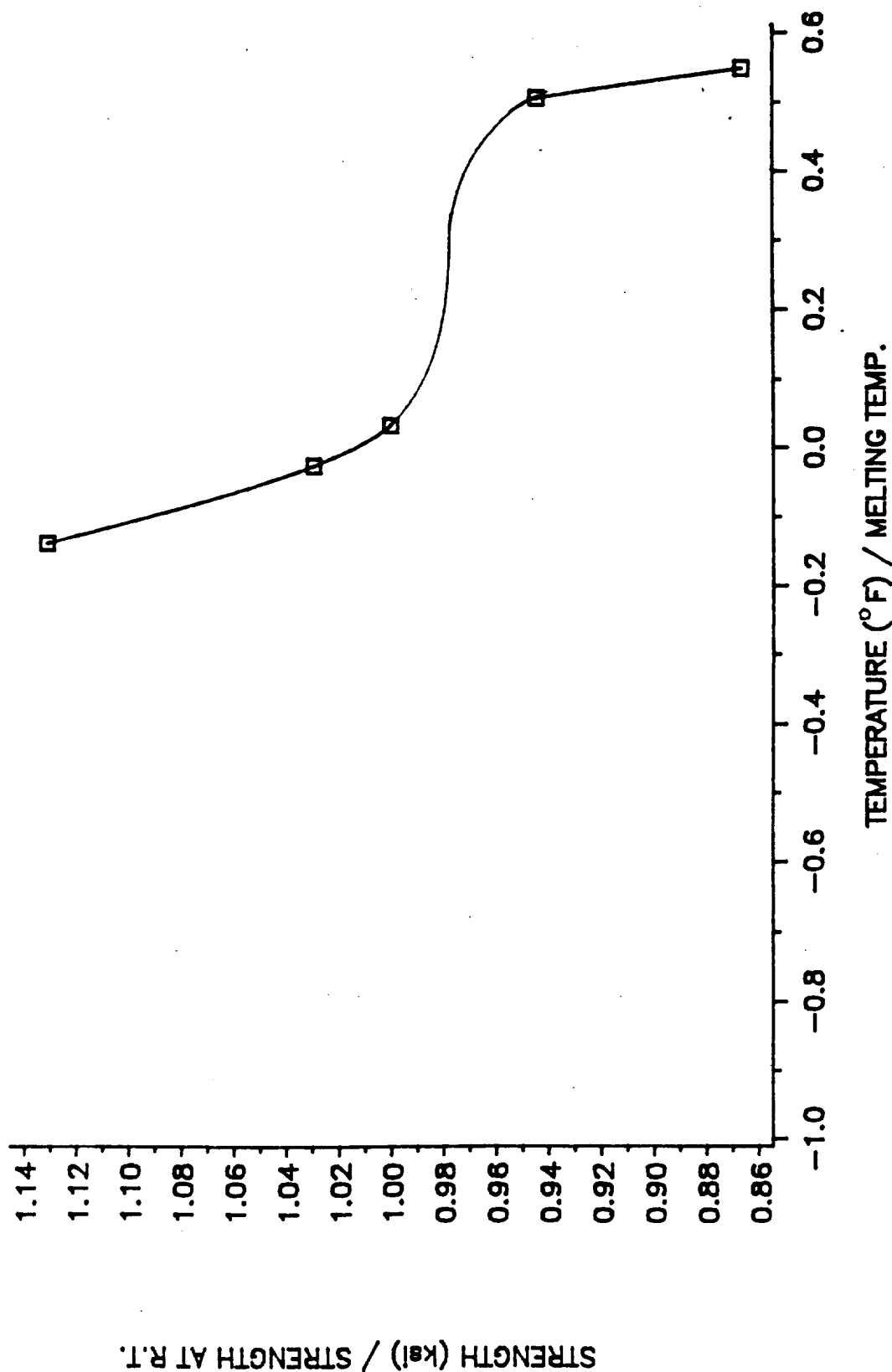
HOT-ROLLED ROUND
ANNEALED AT 1800 °F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



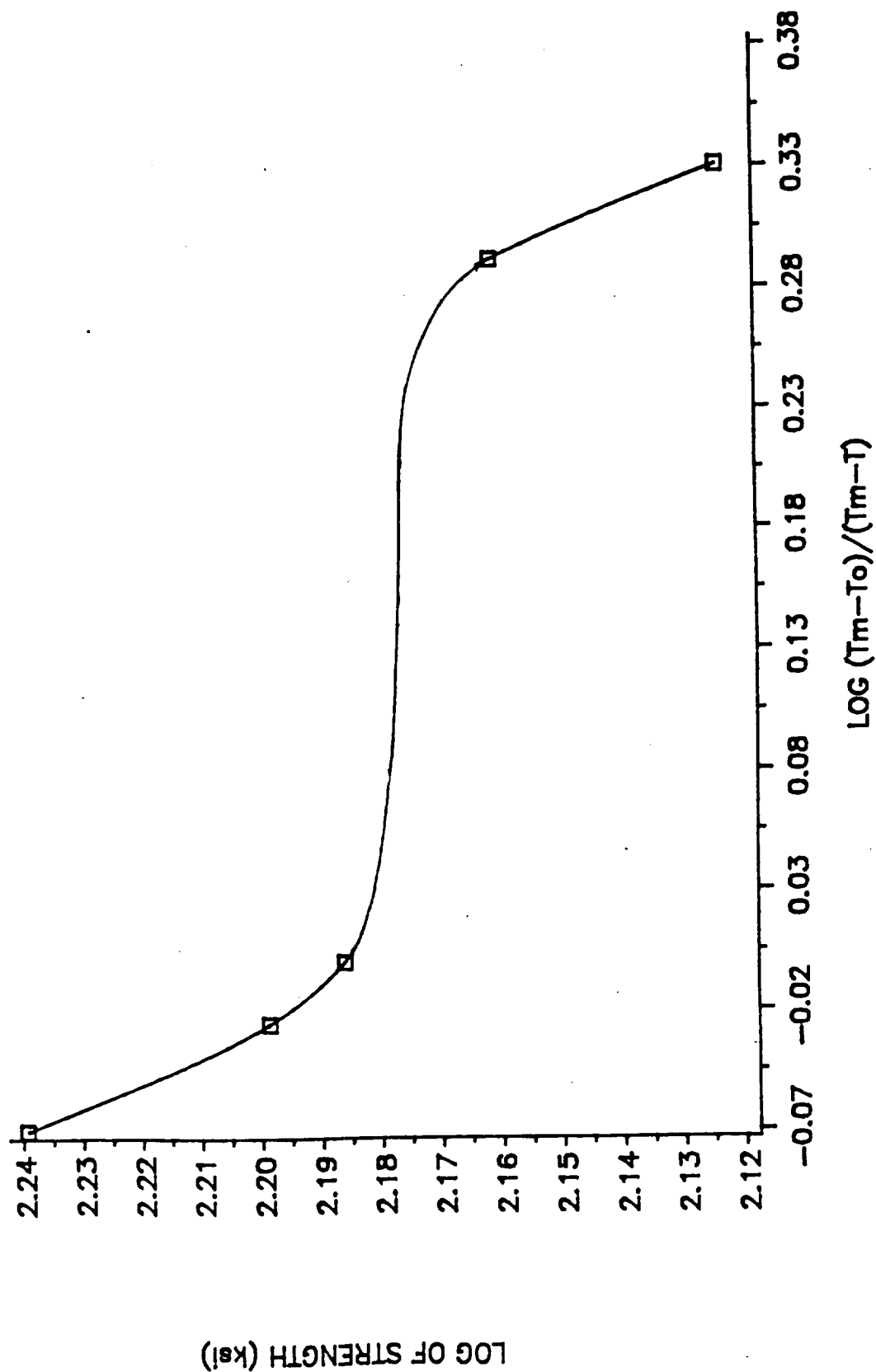
HOT-ROLLED ROUND
ANNEALED AT 1800 F
R.T.=80 F, $T_m=2369$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



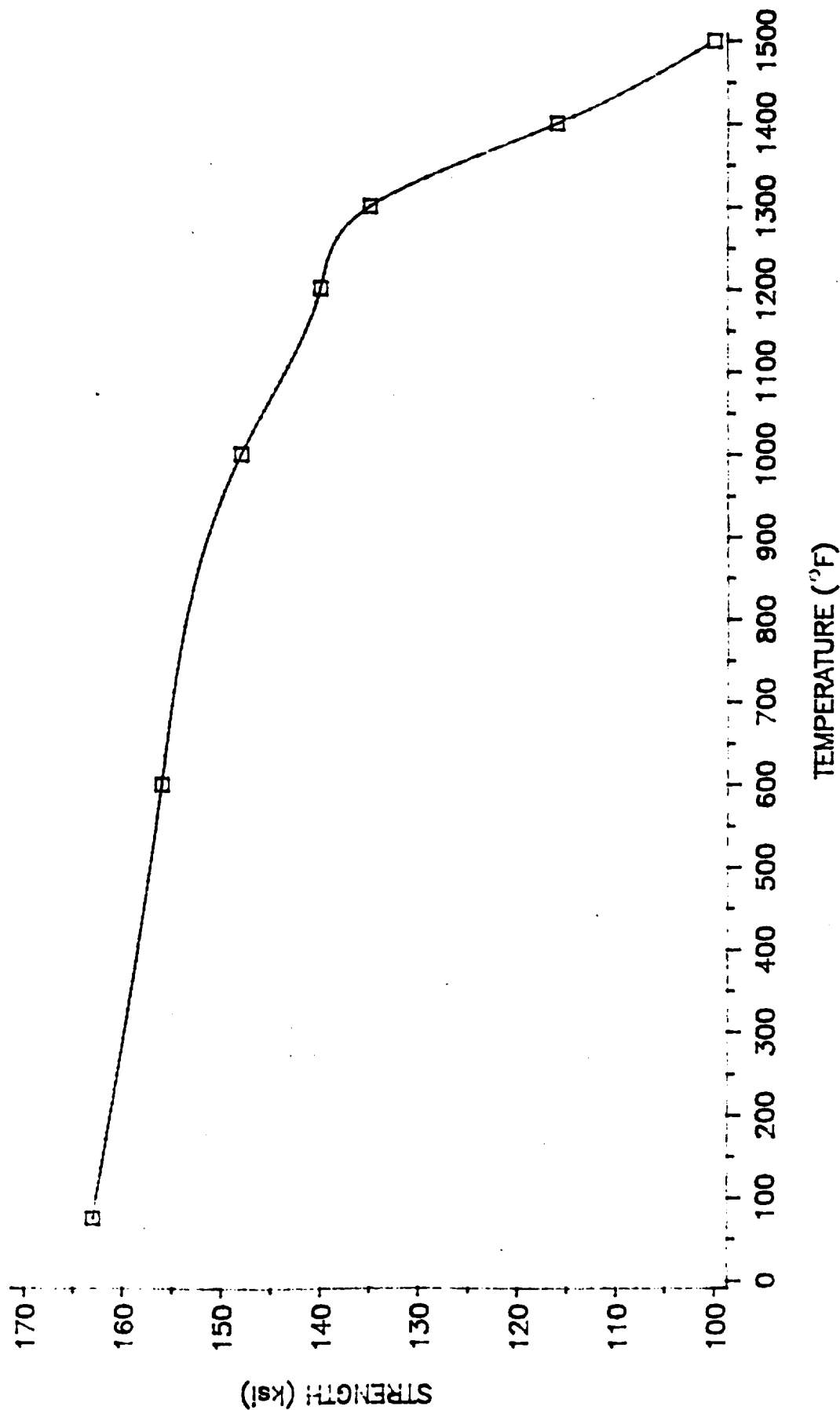
HOT-ROLLED ROUND
ANNEALED AT 1800 F
 $T_0=80$ F, $T_m=2369$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



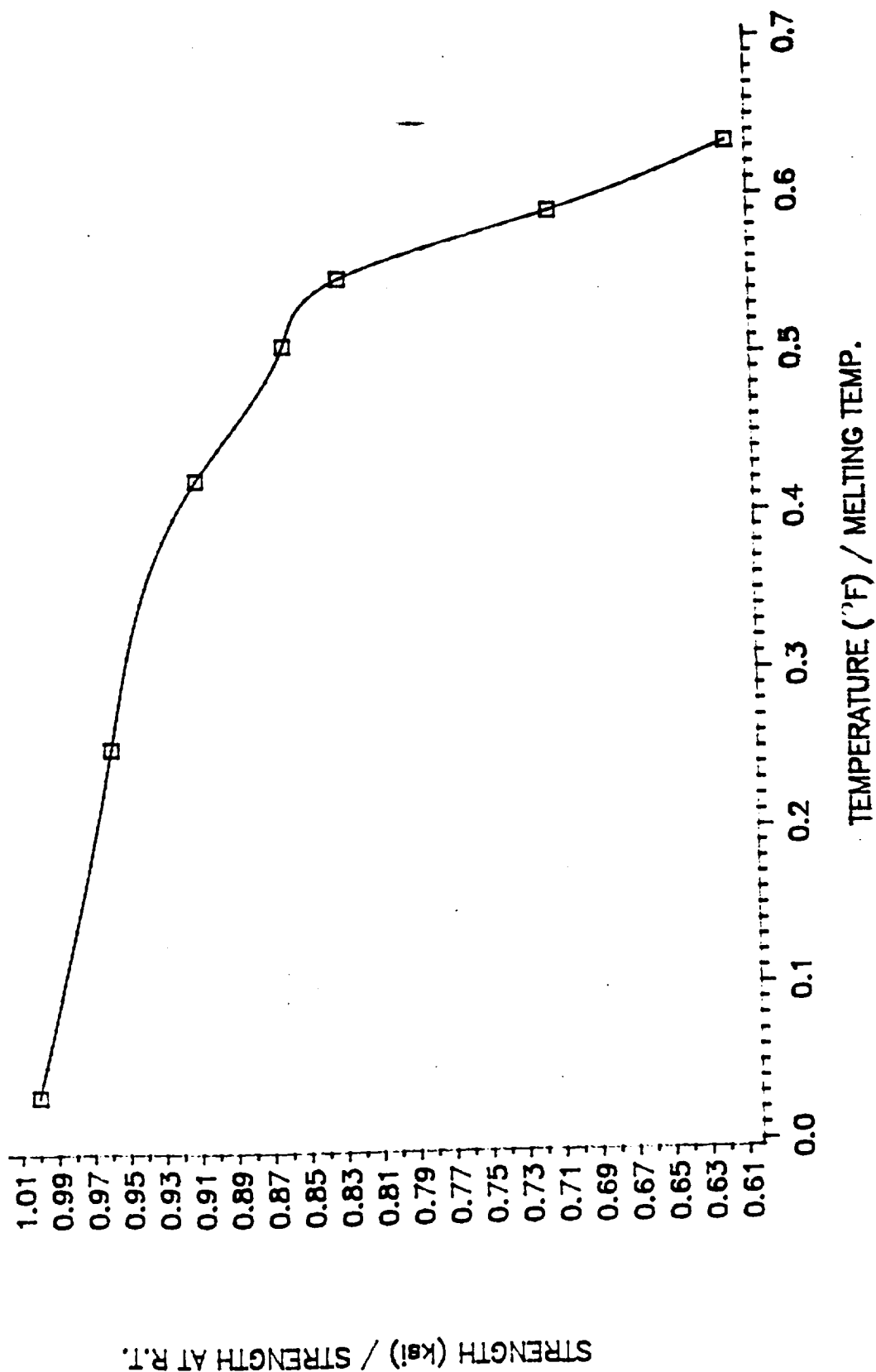
HOT-ROLLED ROUND
ANNEALED AT 1950 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



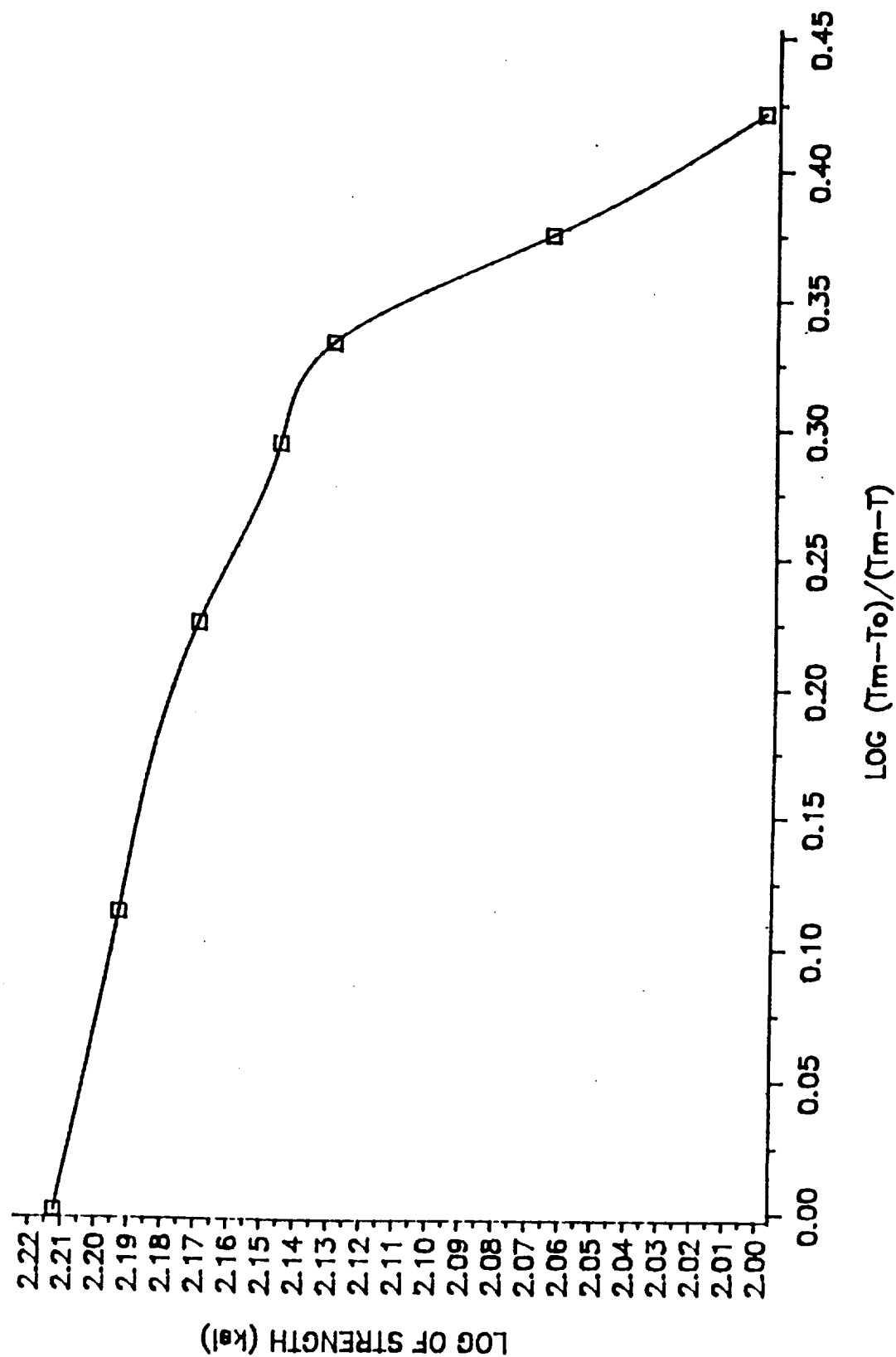
HOT-ROLLED ROUND
ANNEALED AT 1950 F
R.T.=75 F, $T_m=2369$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718

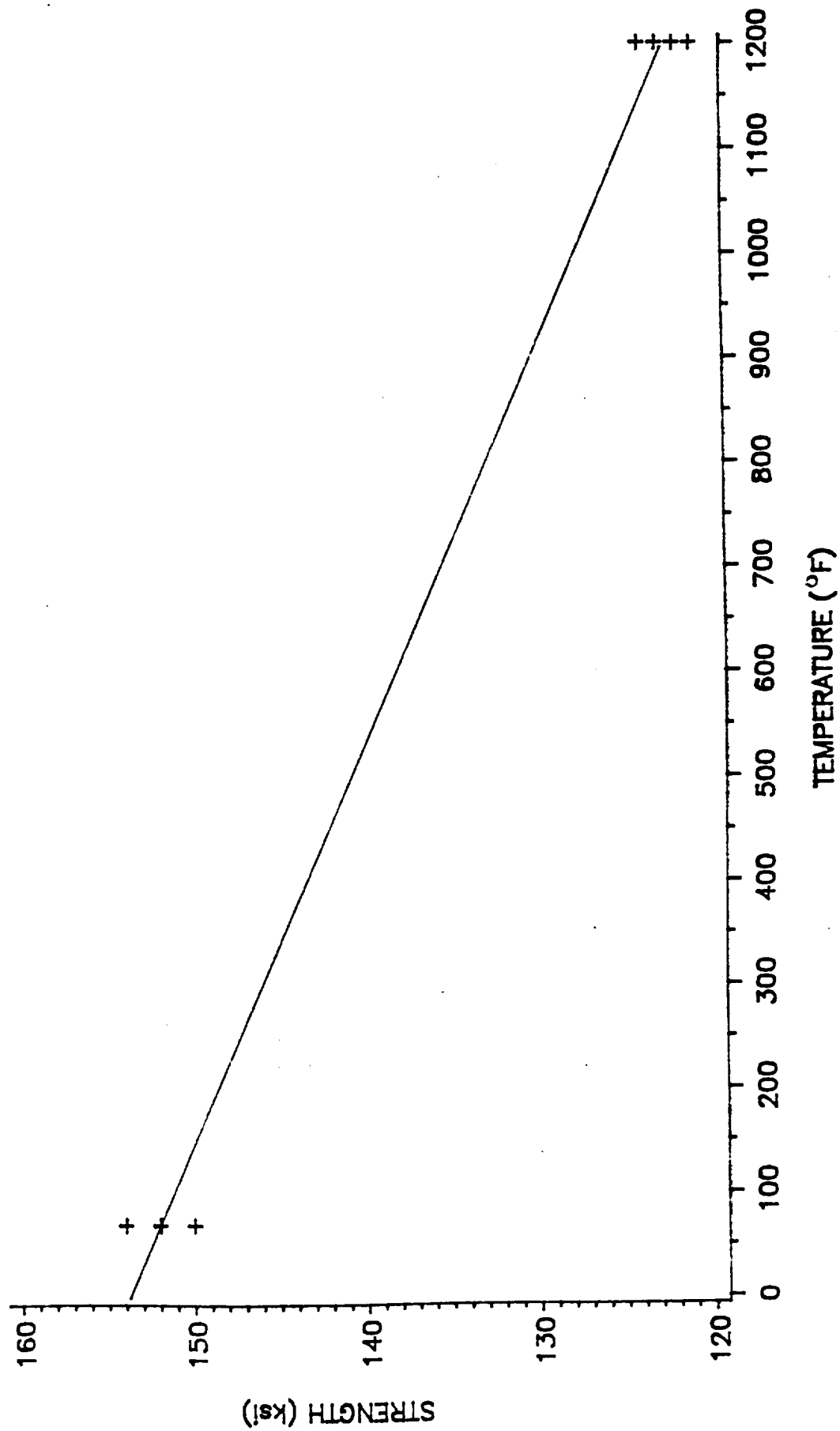


HOT-ROLLED ROUND
ANNEALED AT 1950 F
 $T_0=75$ F, $T_m=2369$ F

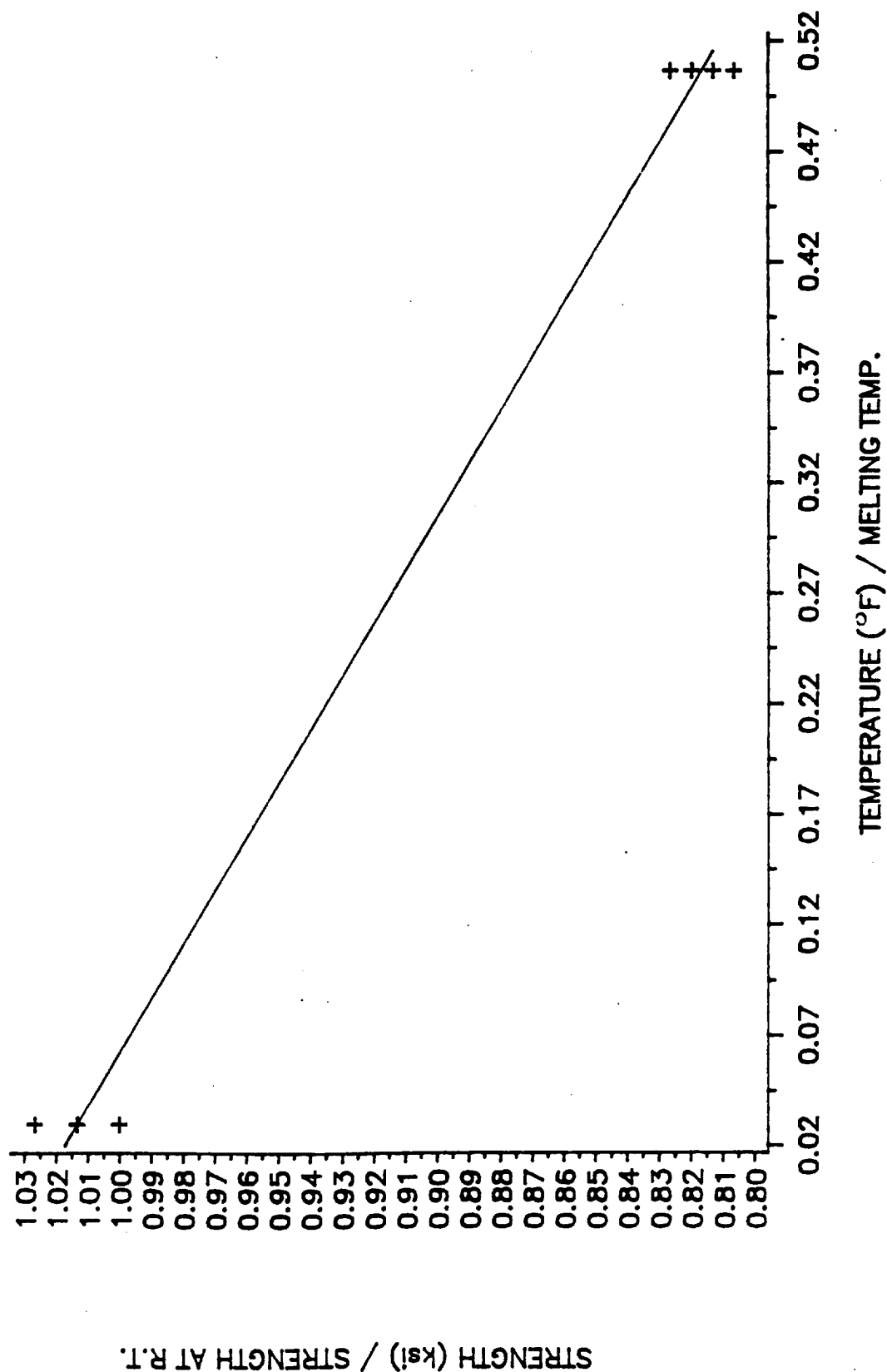
EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718

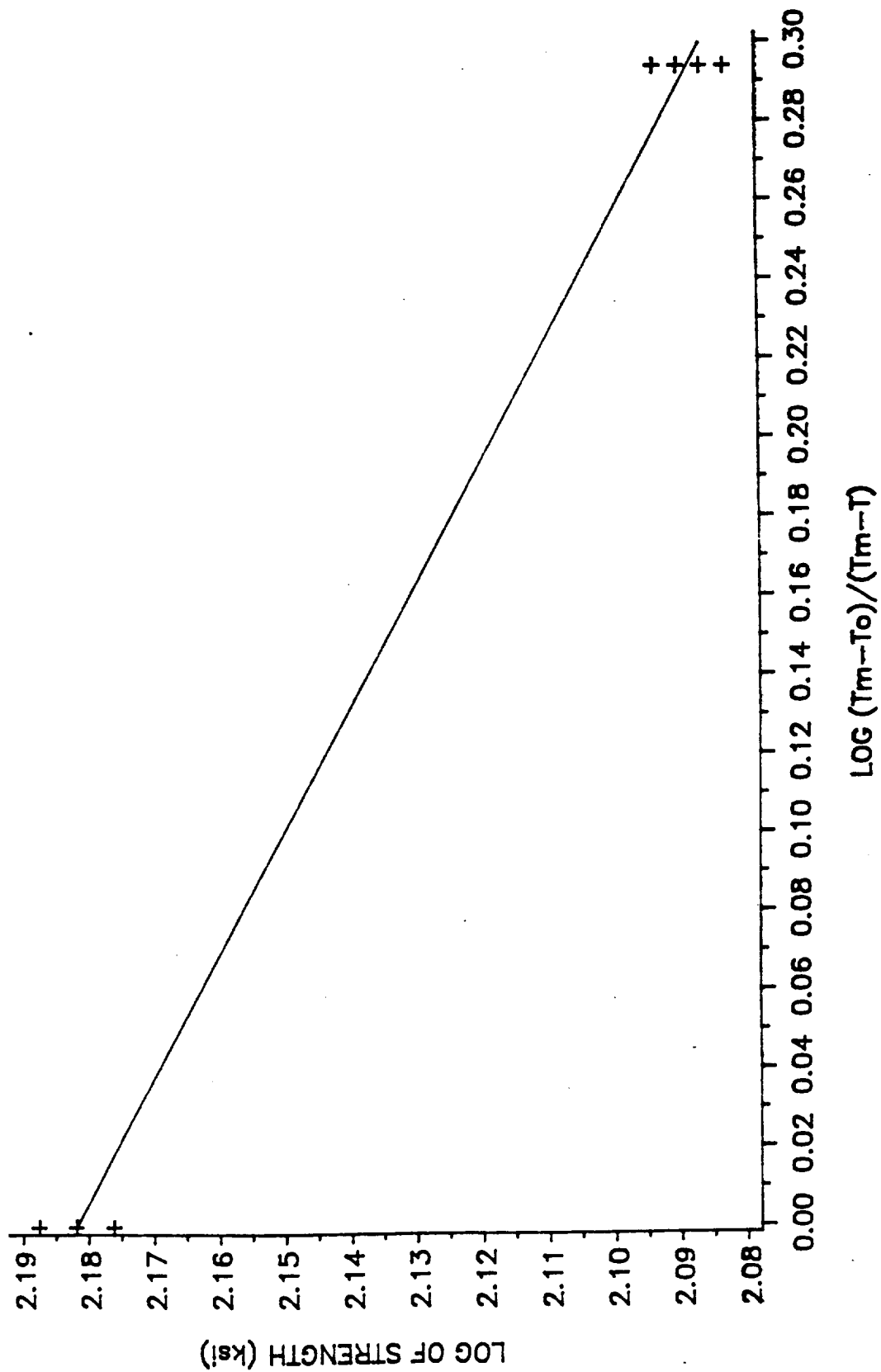


EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



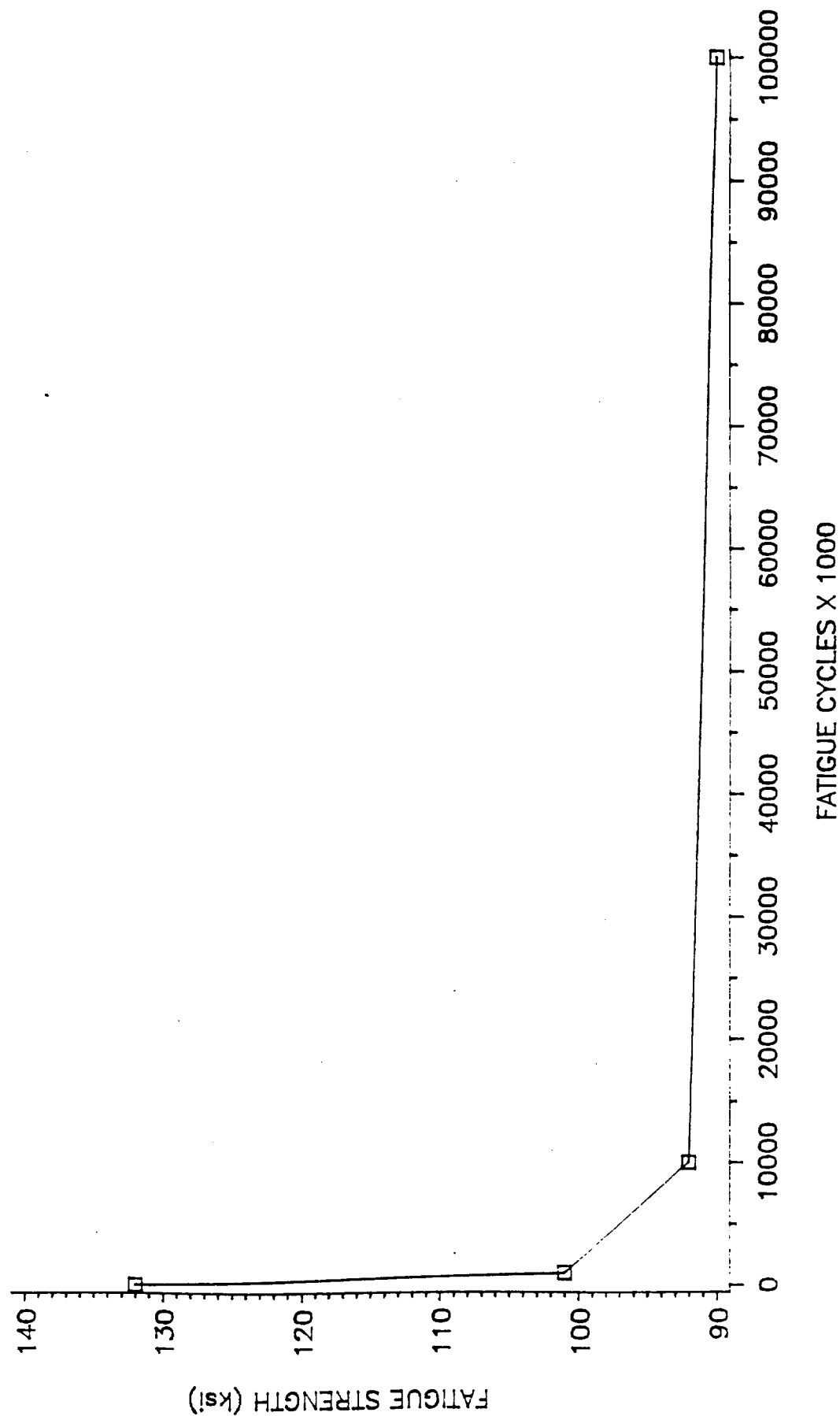
$T_0=70$ F, $T_m=2369$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 718



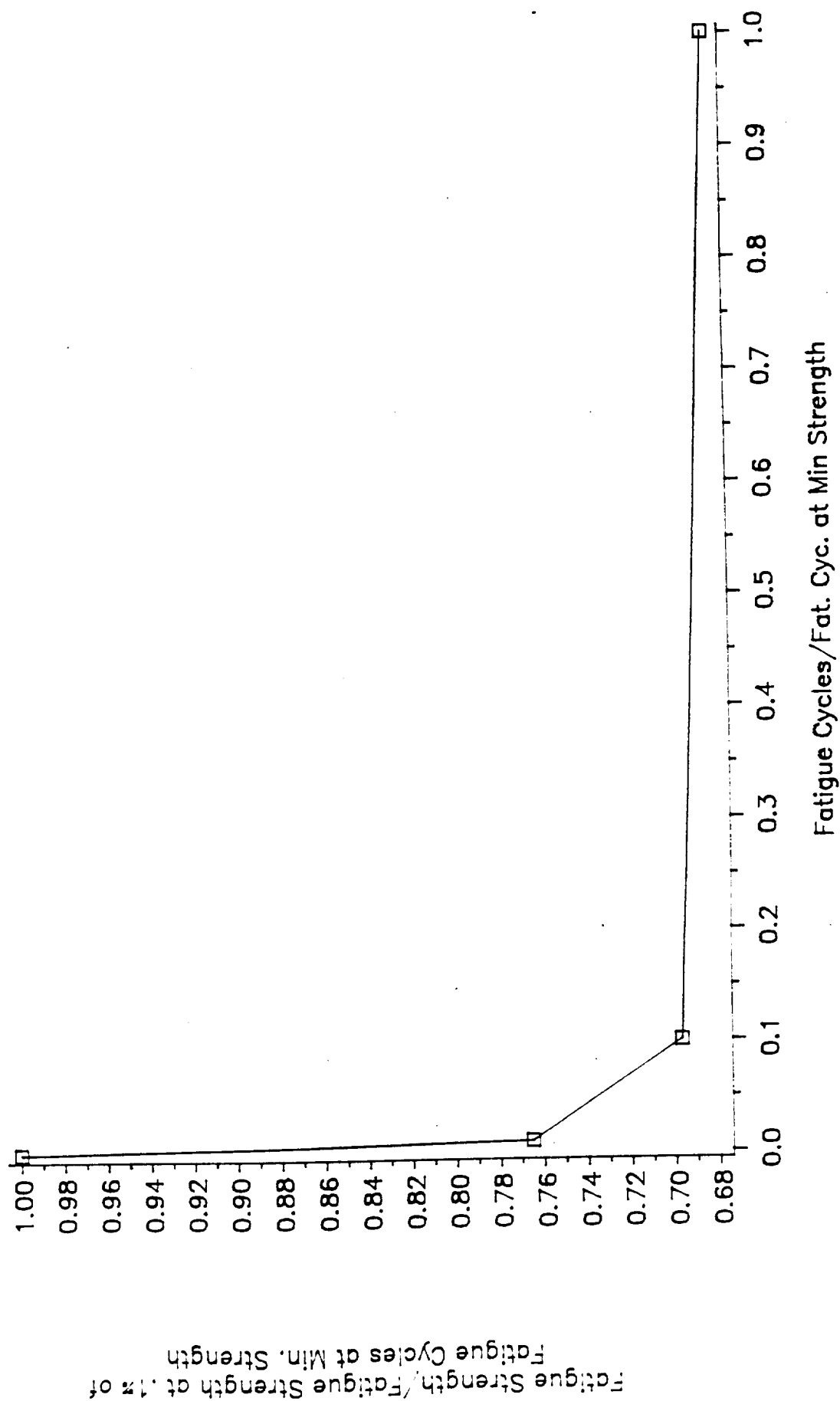
TEST TEMP. = 75 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



TEST TEMP. = 75 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718

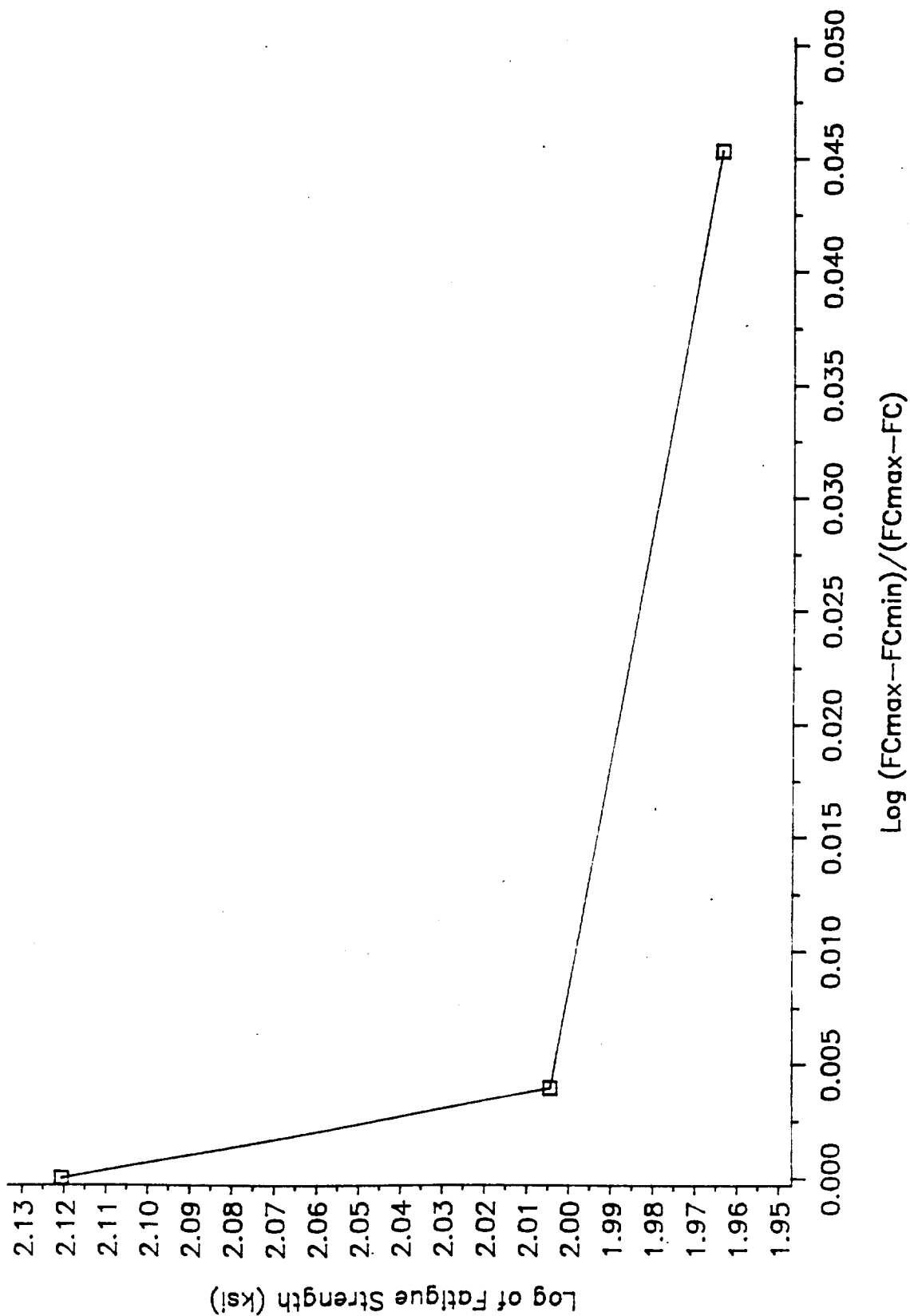


Fatigue Strength/Fatigue Strength at .1% of
Fatigue Cycles at Min. Strength

Fatigue Cycles/Fat. Cyc. at Min Strength

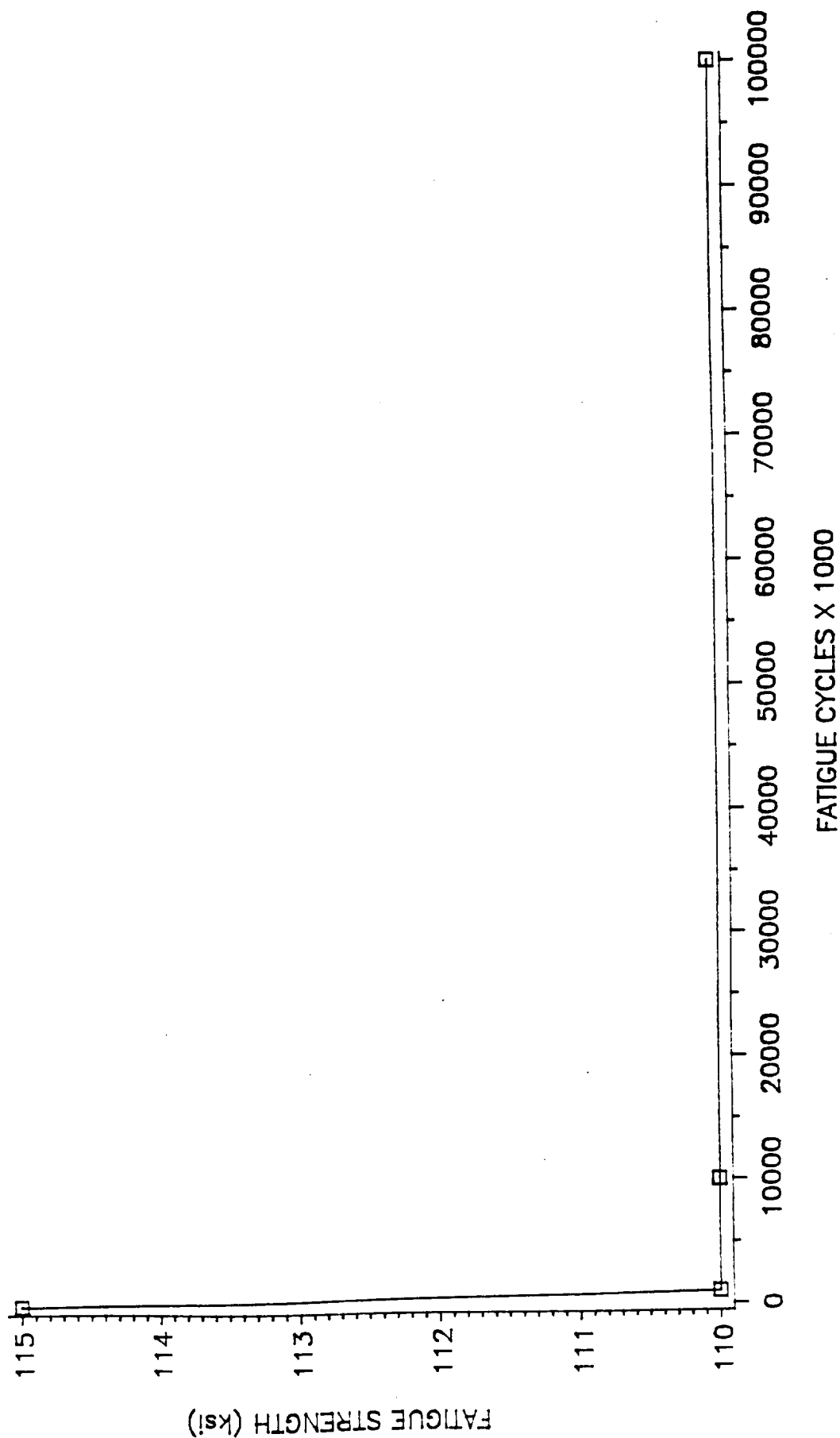
TEST TEMP. = 75 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



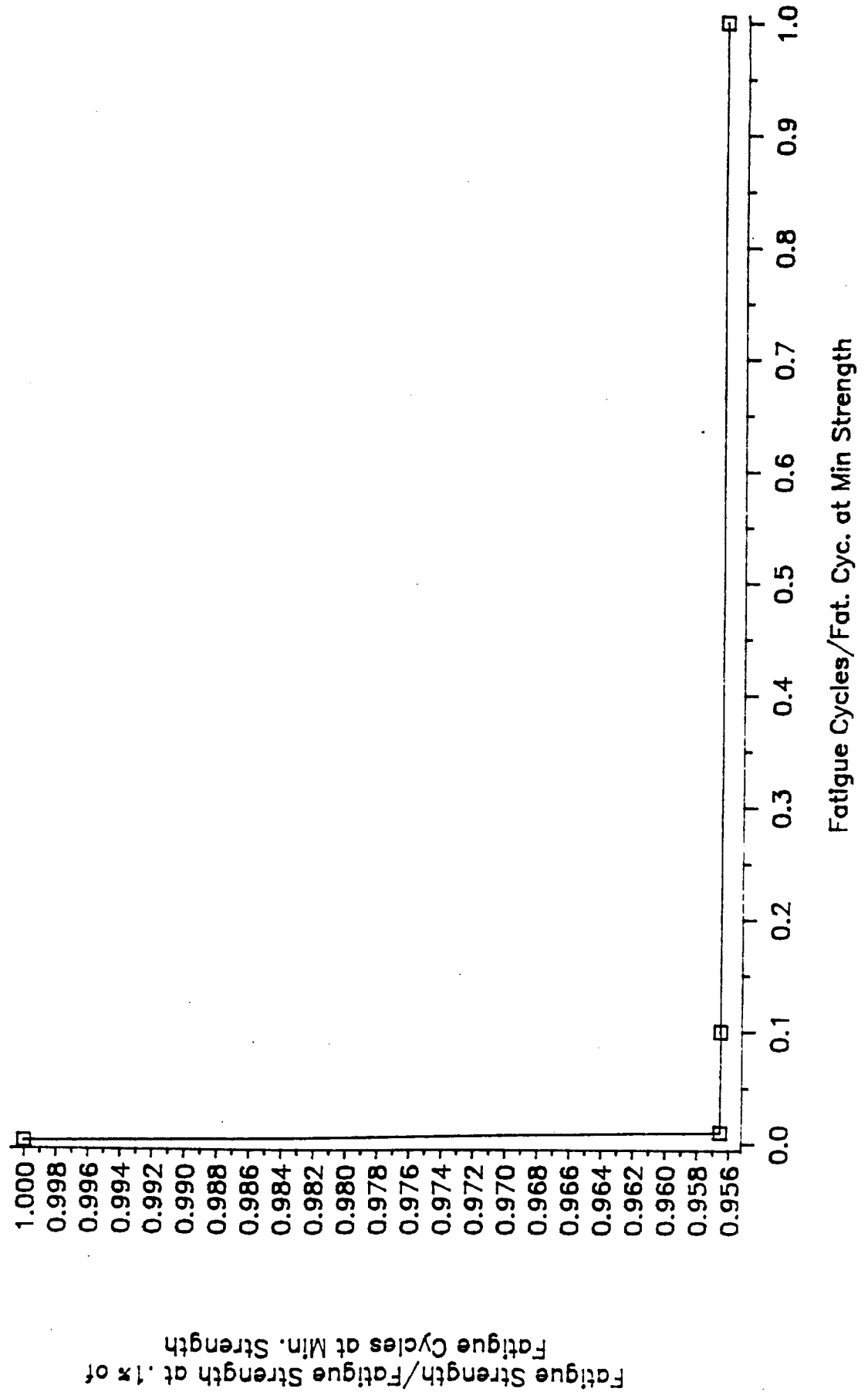
TEST TEMP. = 600 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



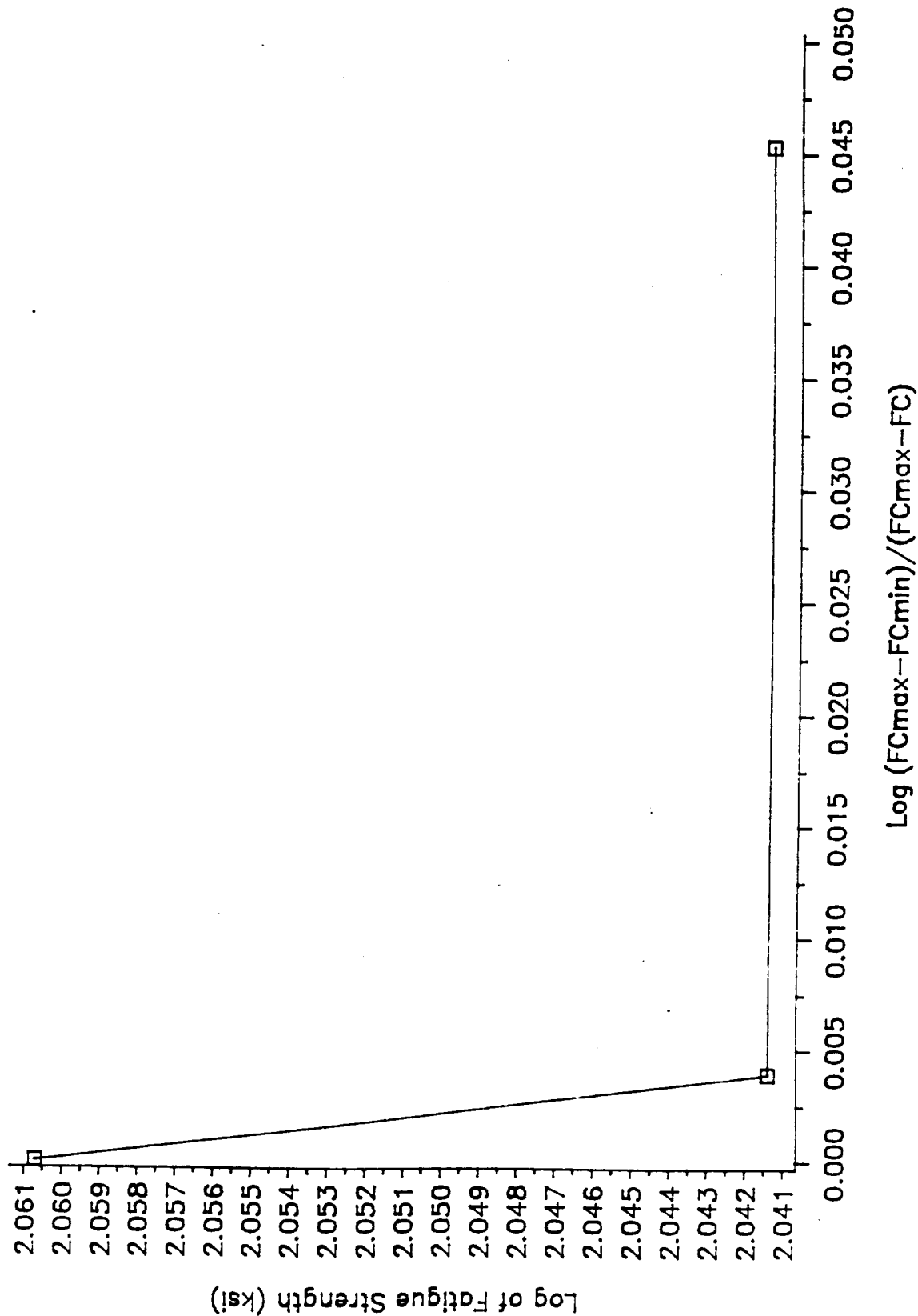
TEST TEMP. = 600 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



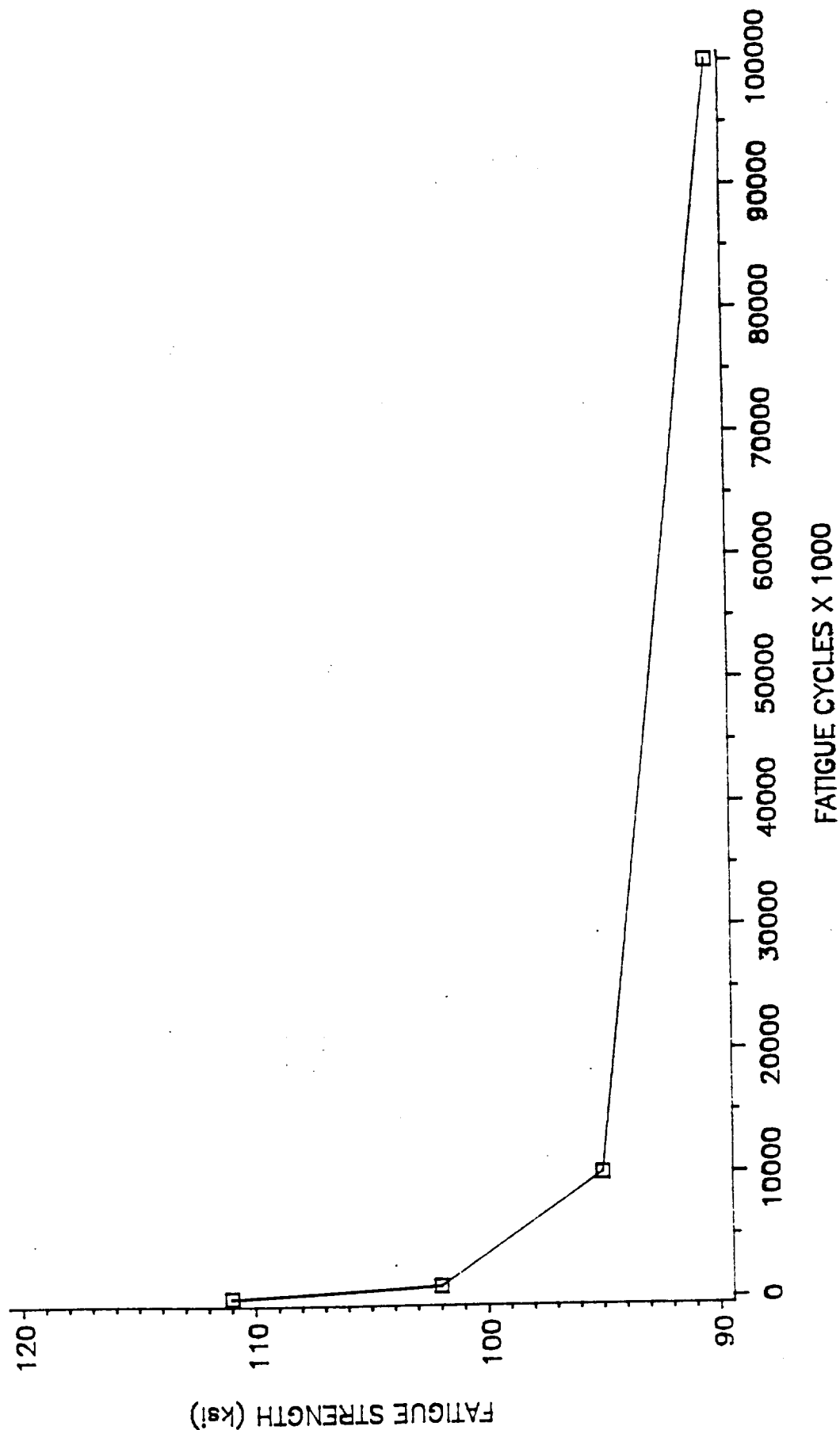
TEST TEMP. = 800 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



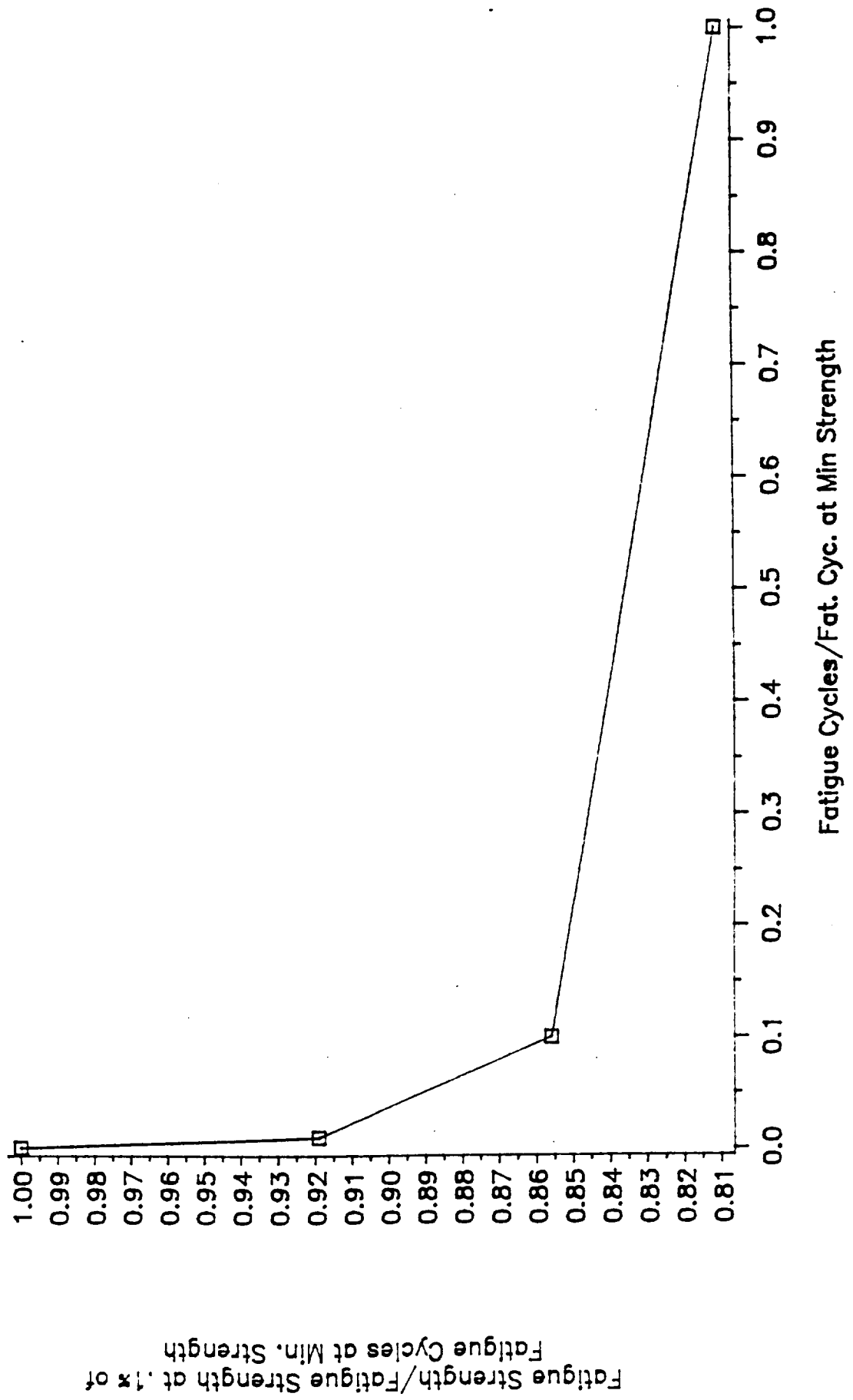
TEST TEMP. = 1000 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



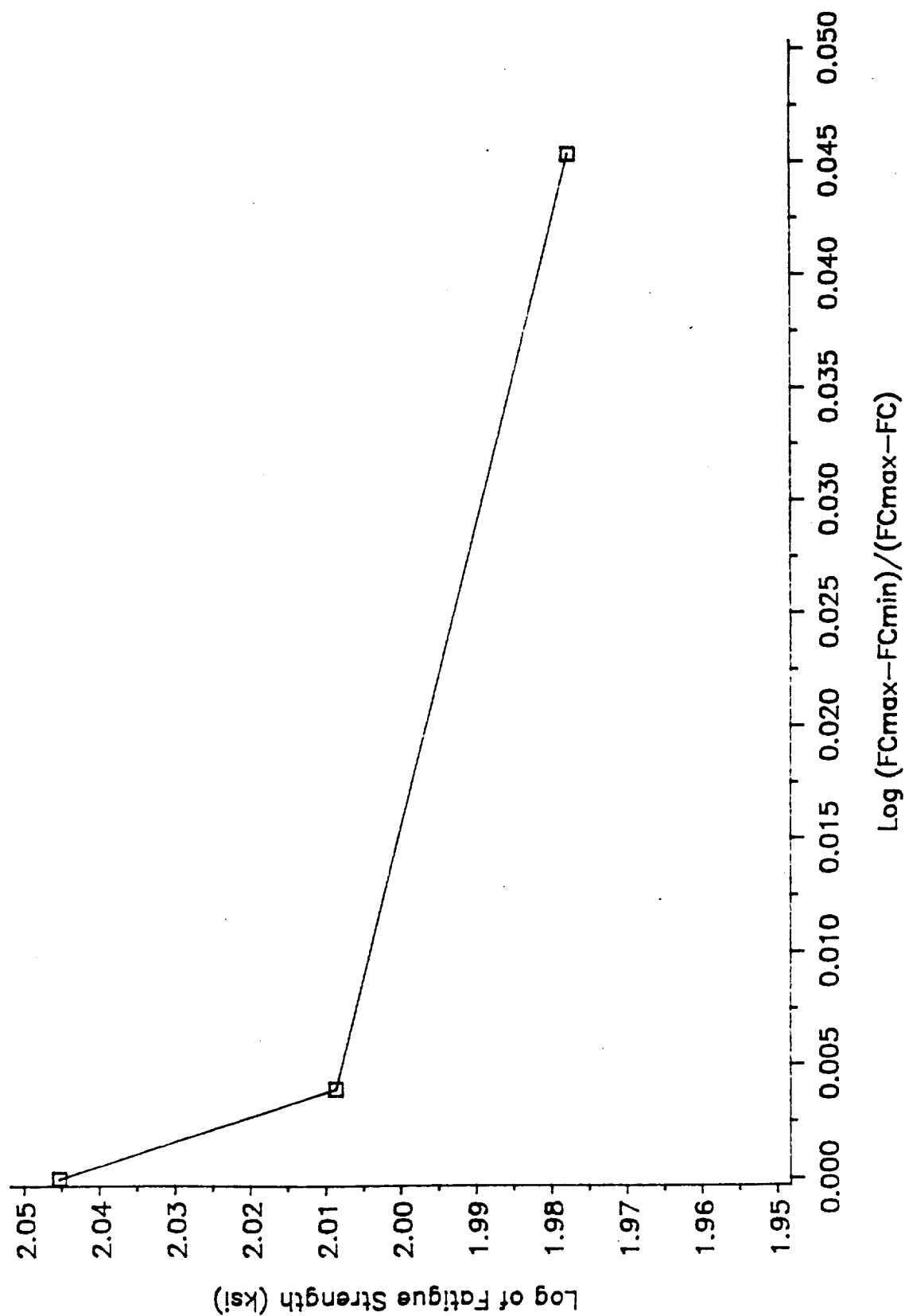
TEST TEMP. = 1000 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



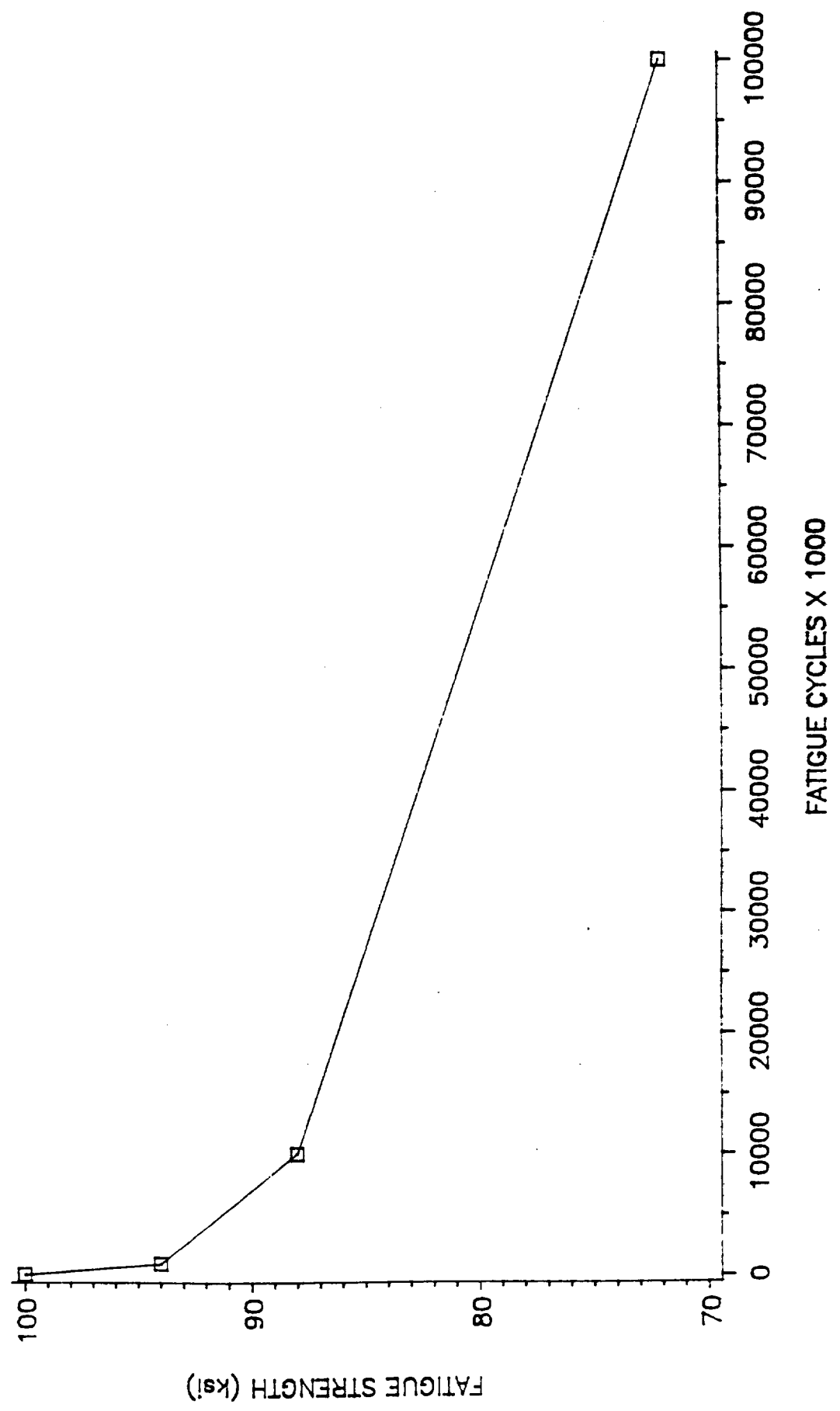
TEST TEMP. = 1000 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



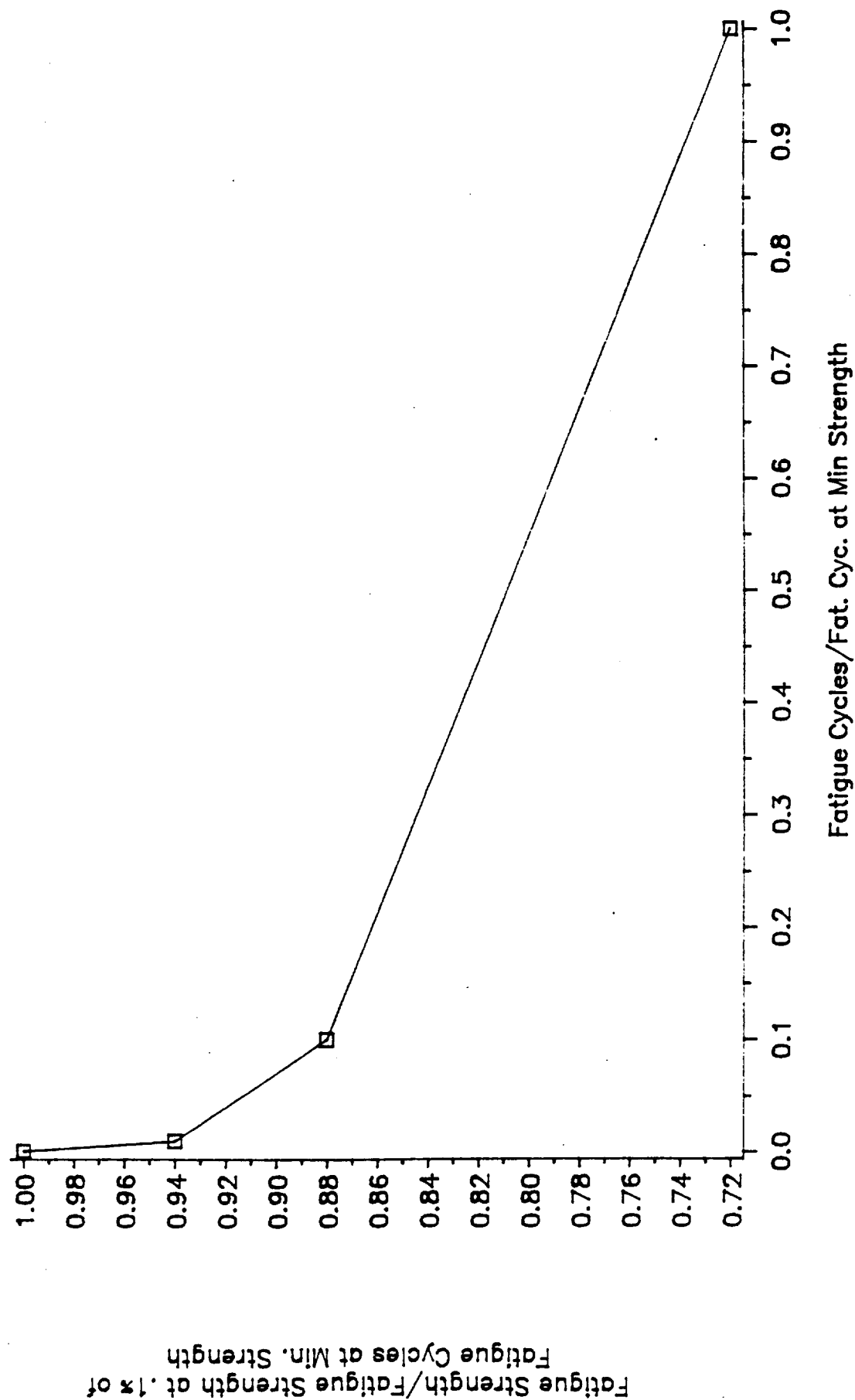
TEST TEMP. = 1200 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



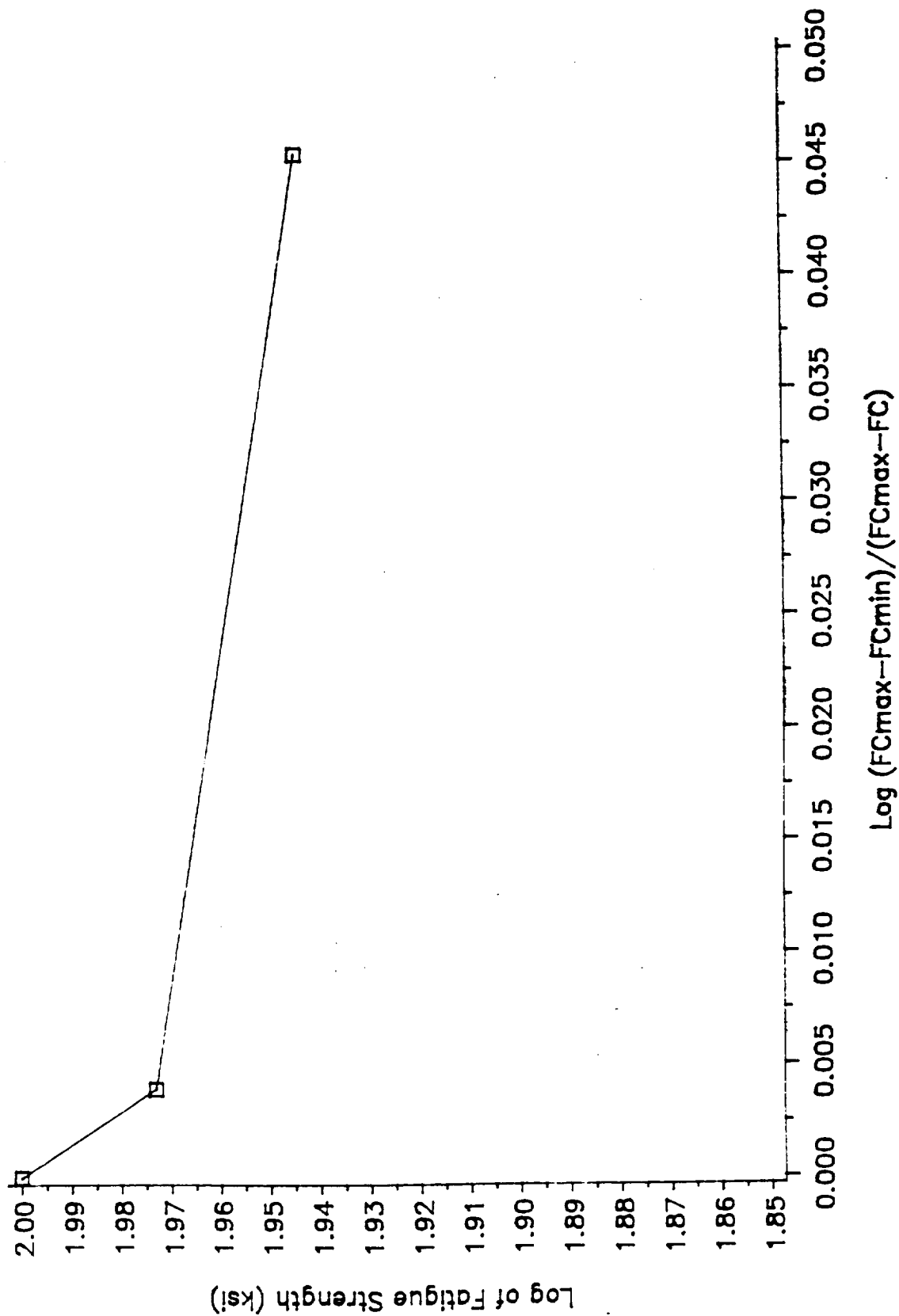
TEST TEMP. = 1200 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



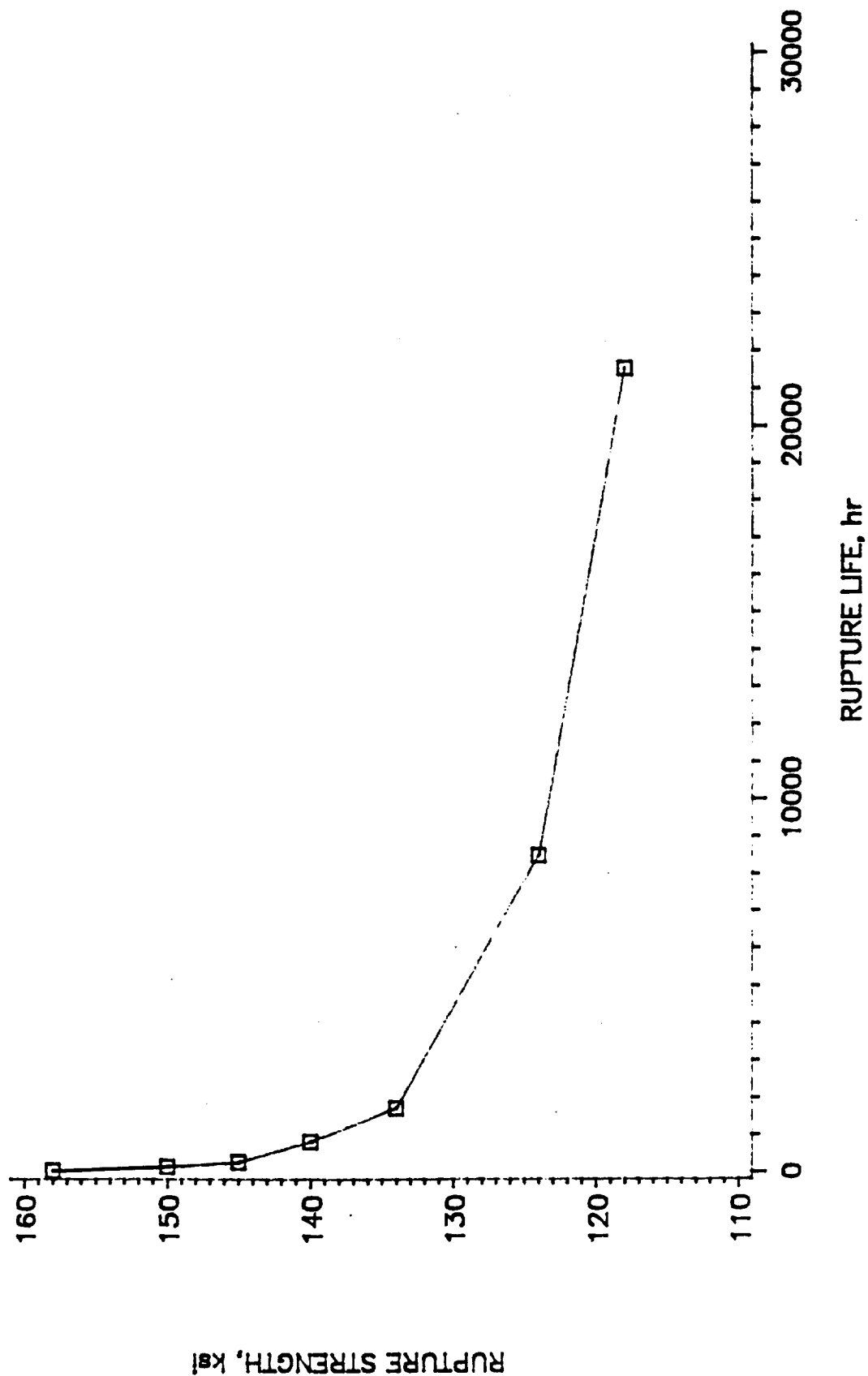
TEST TEMP. = 1200 F

EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 718



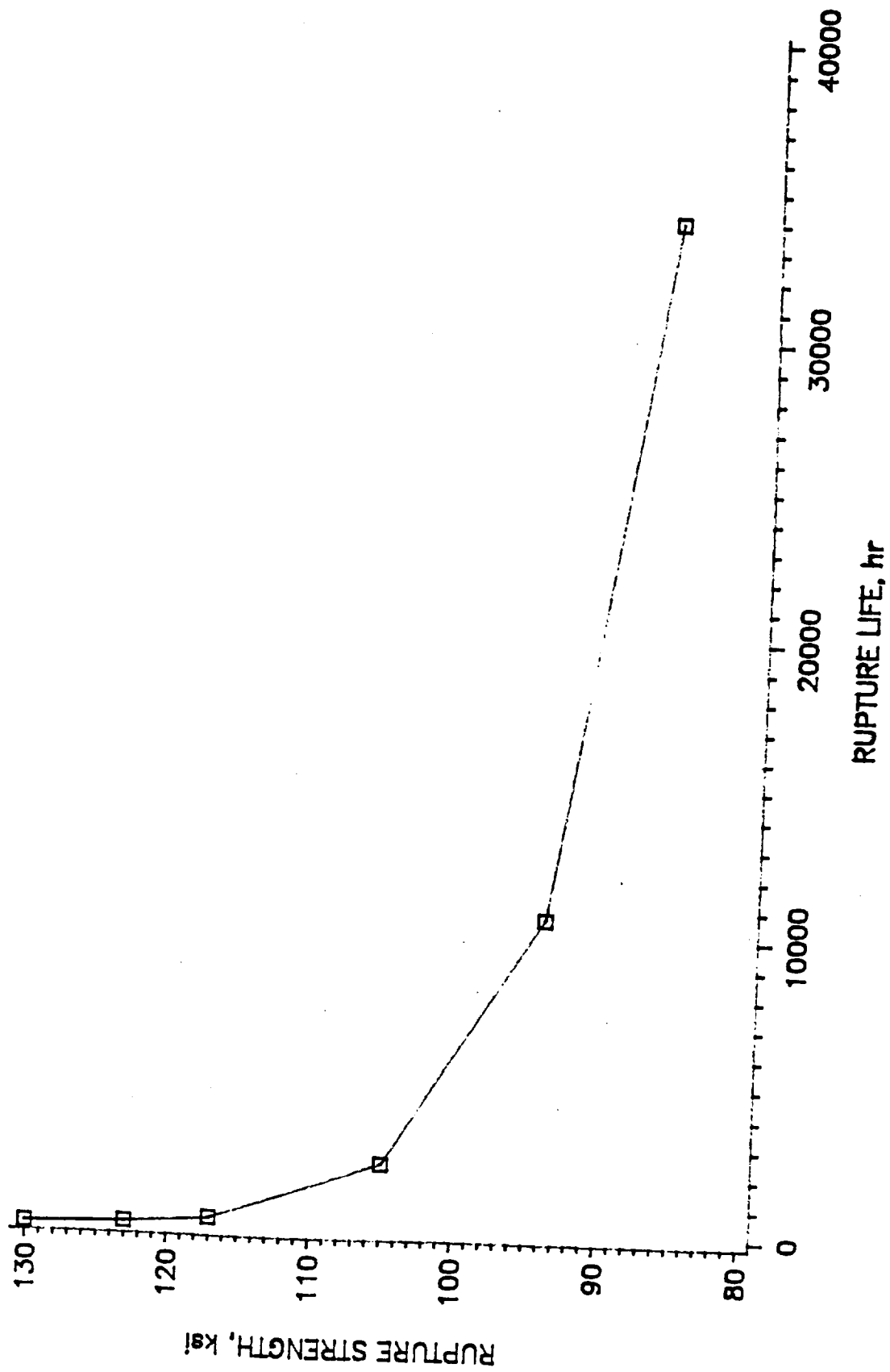
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



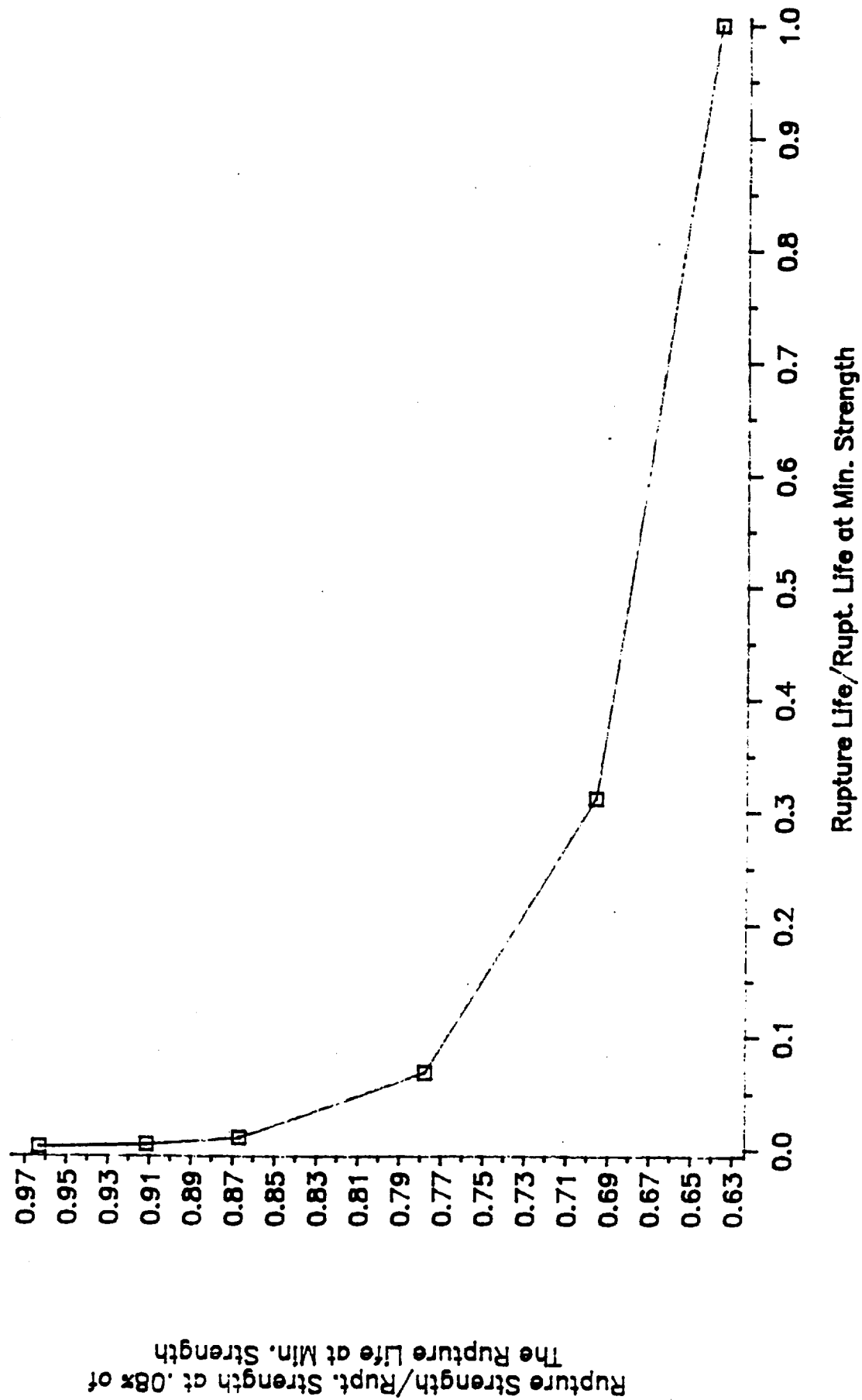
TEST TEMP. = 1100 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



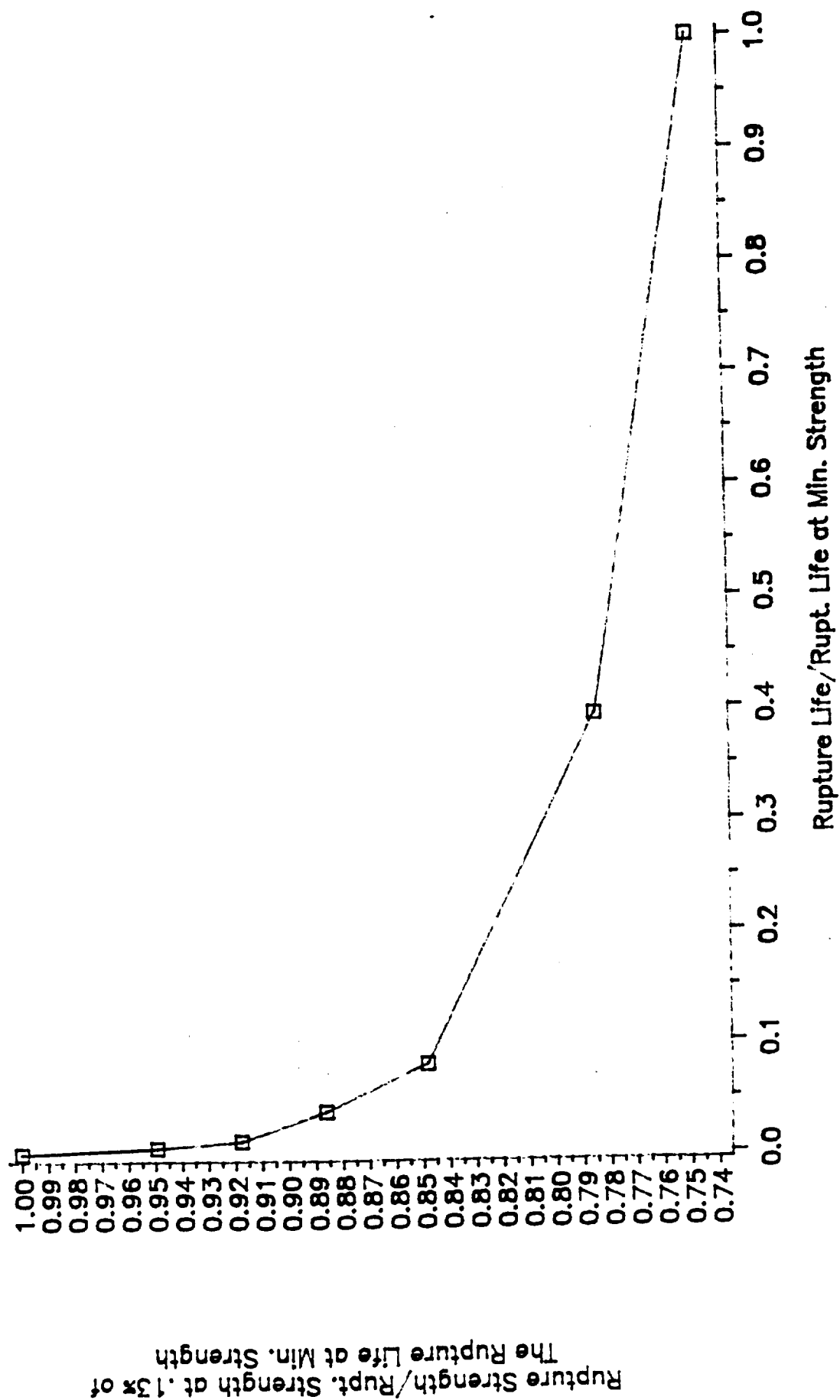
TEST TEMP. = 1100 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



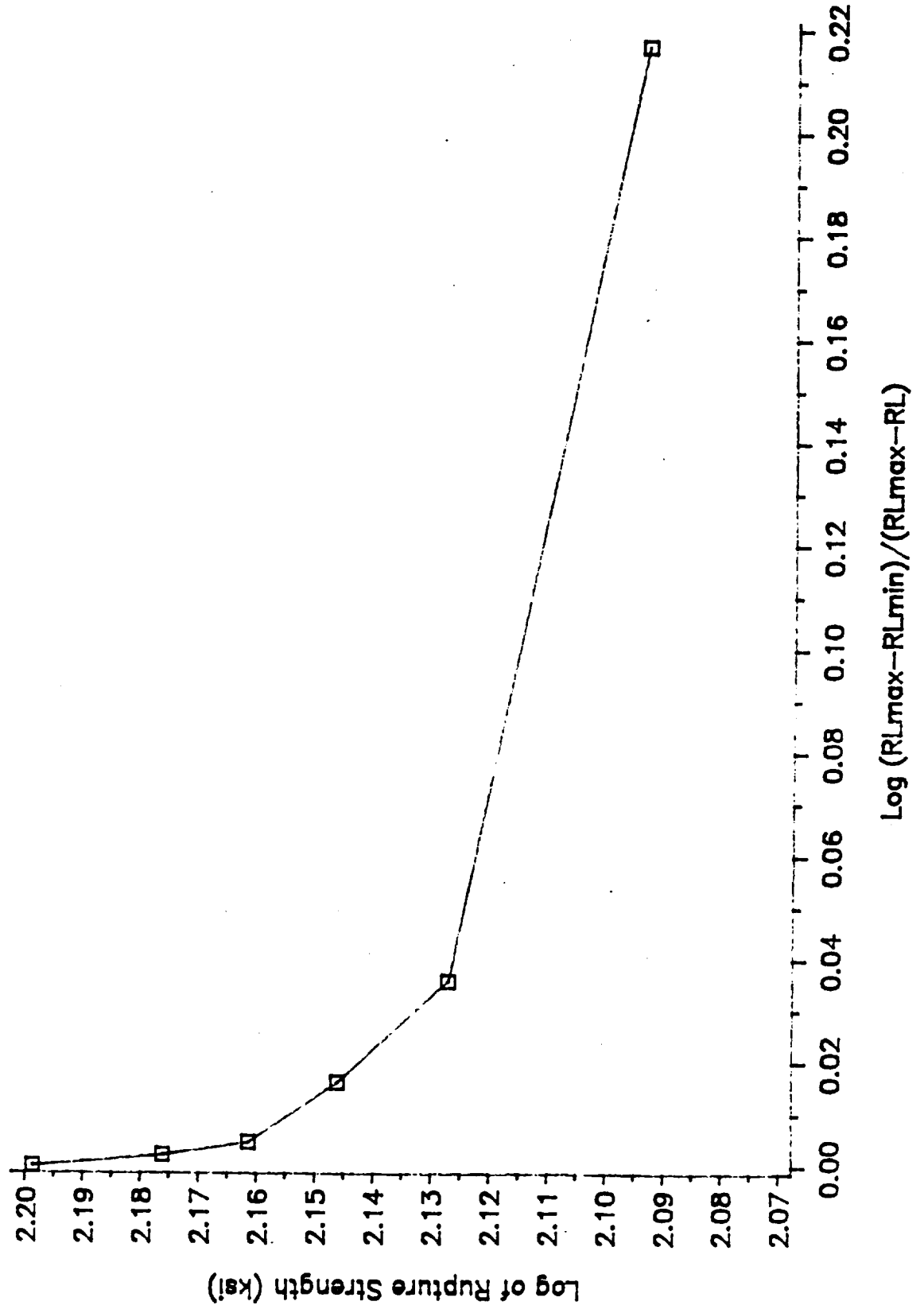
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



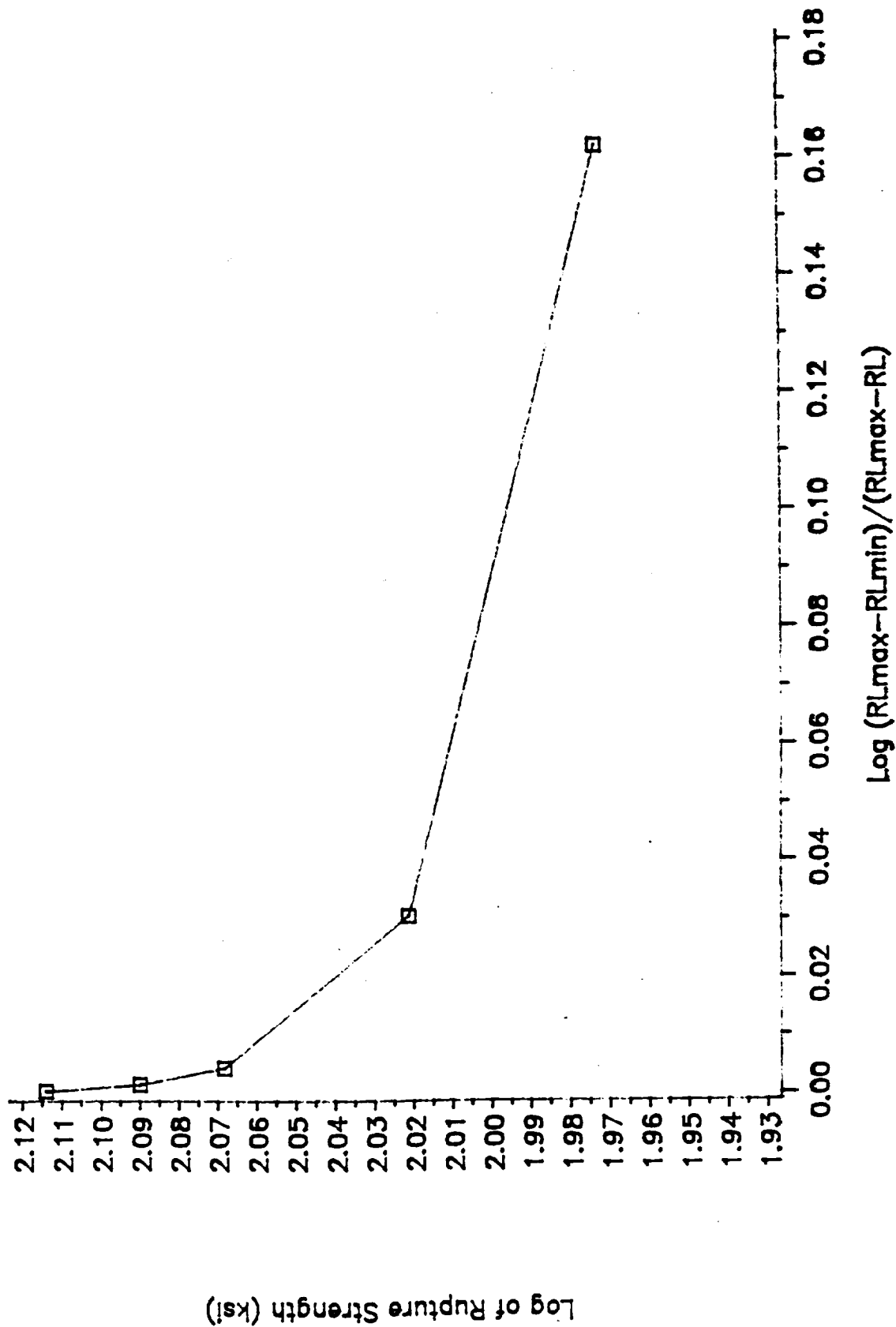
TEST TEMP. -- 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



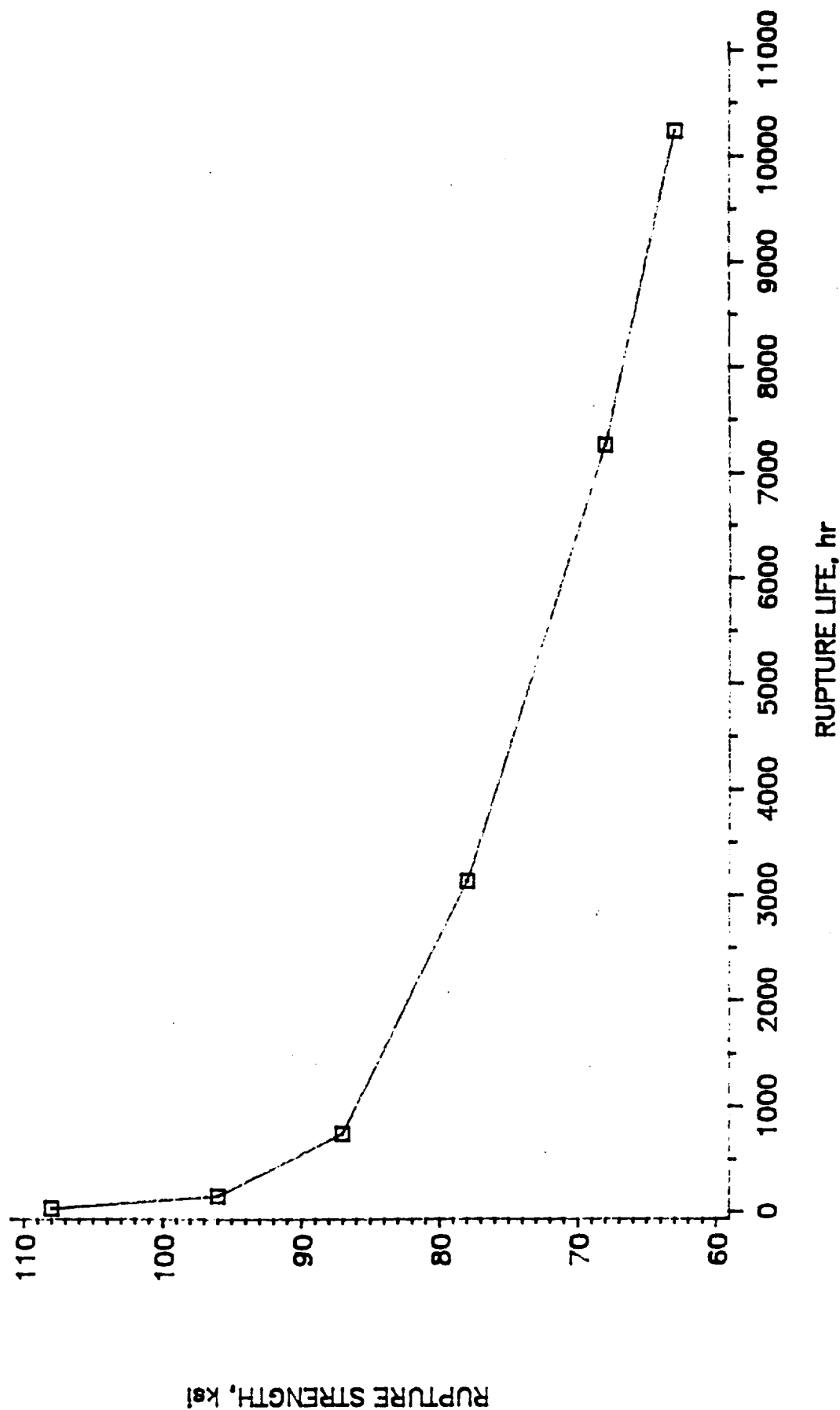
TEST TEMP. = 1100 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



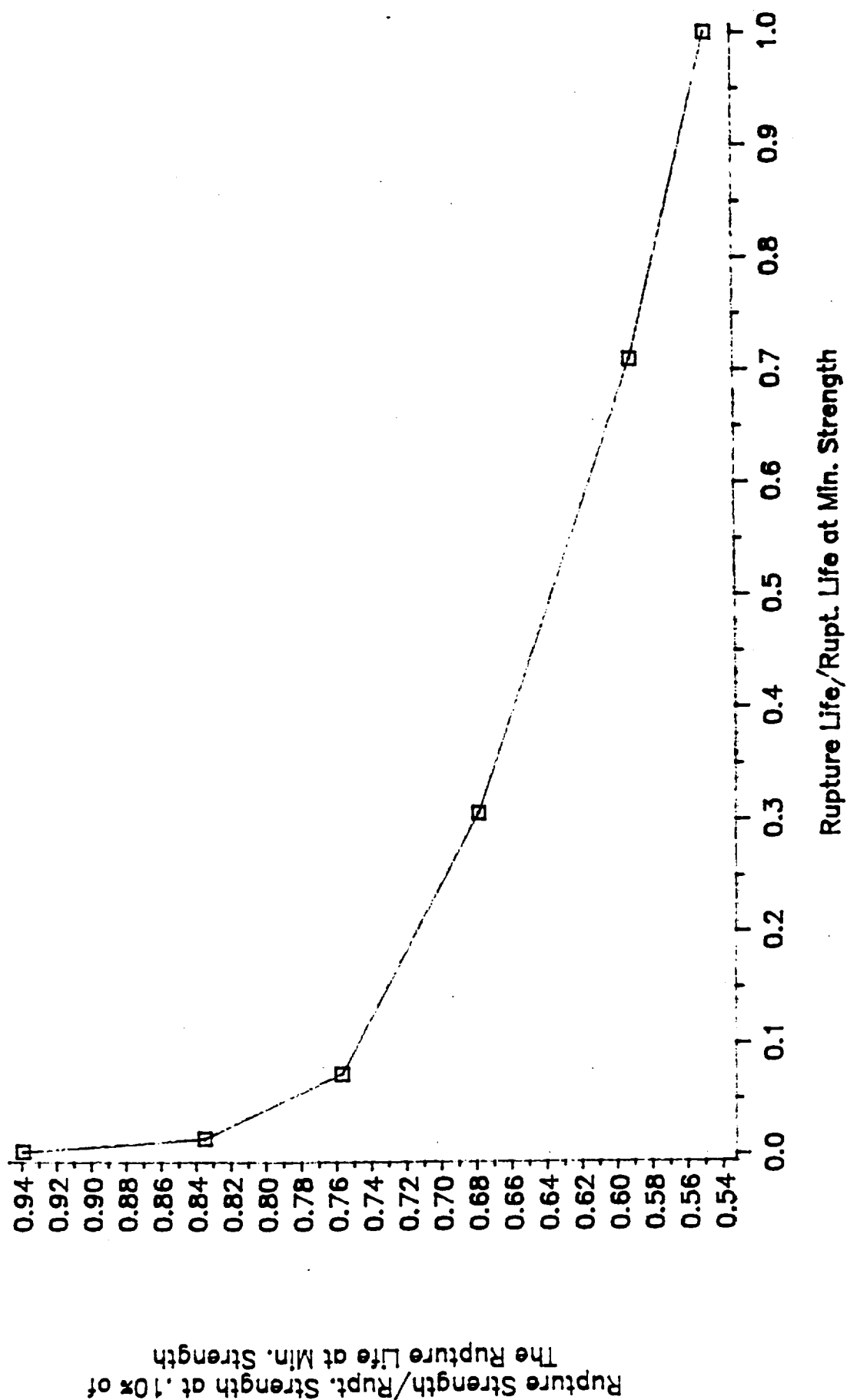
TEST TEMP. -- 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



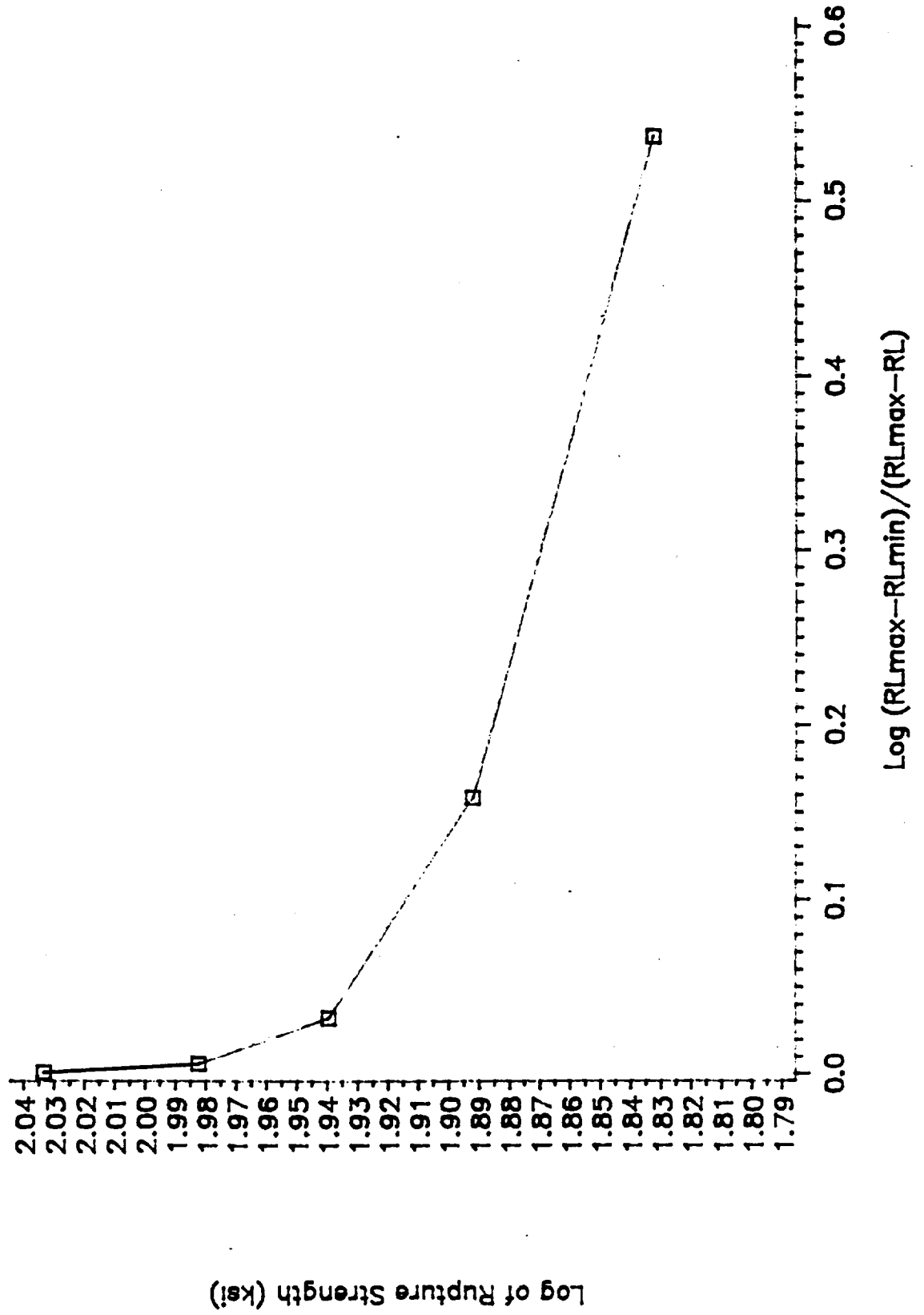
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



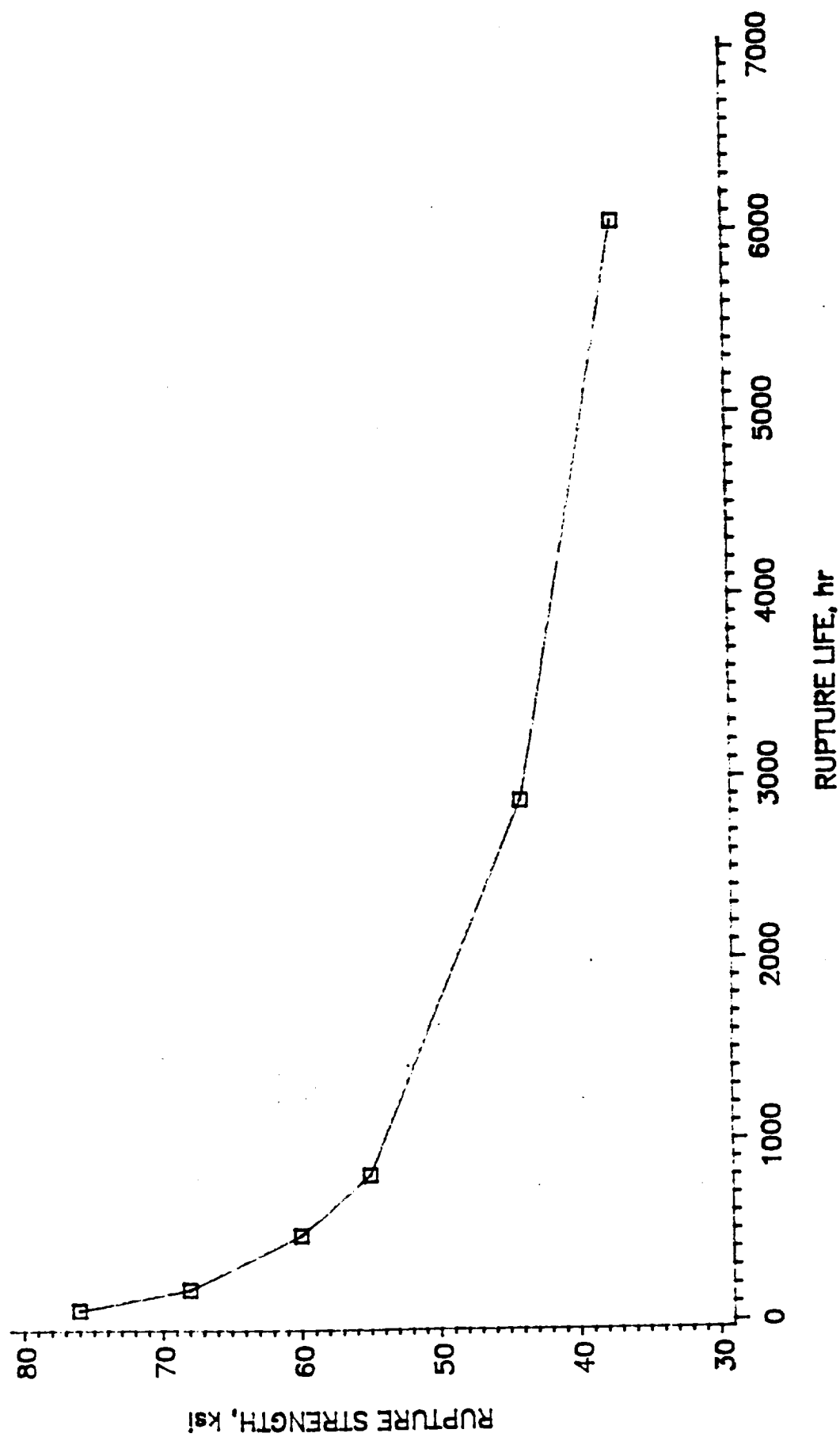
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



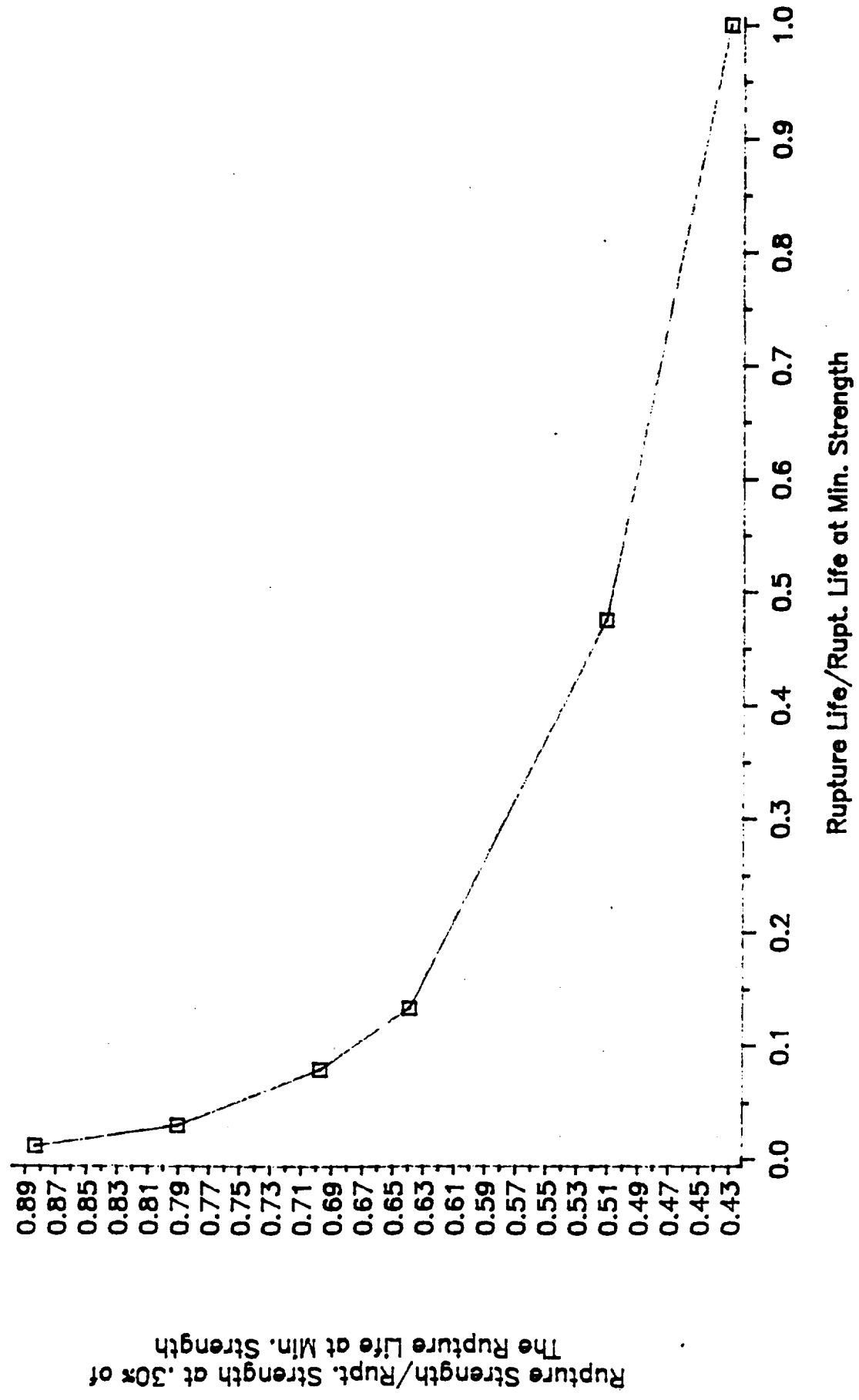
TEST TEMP. = 1300 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



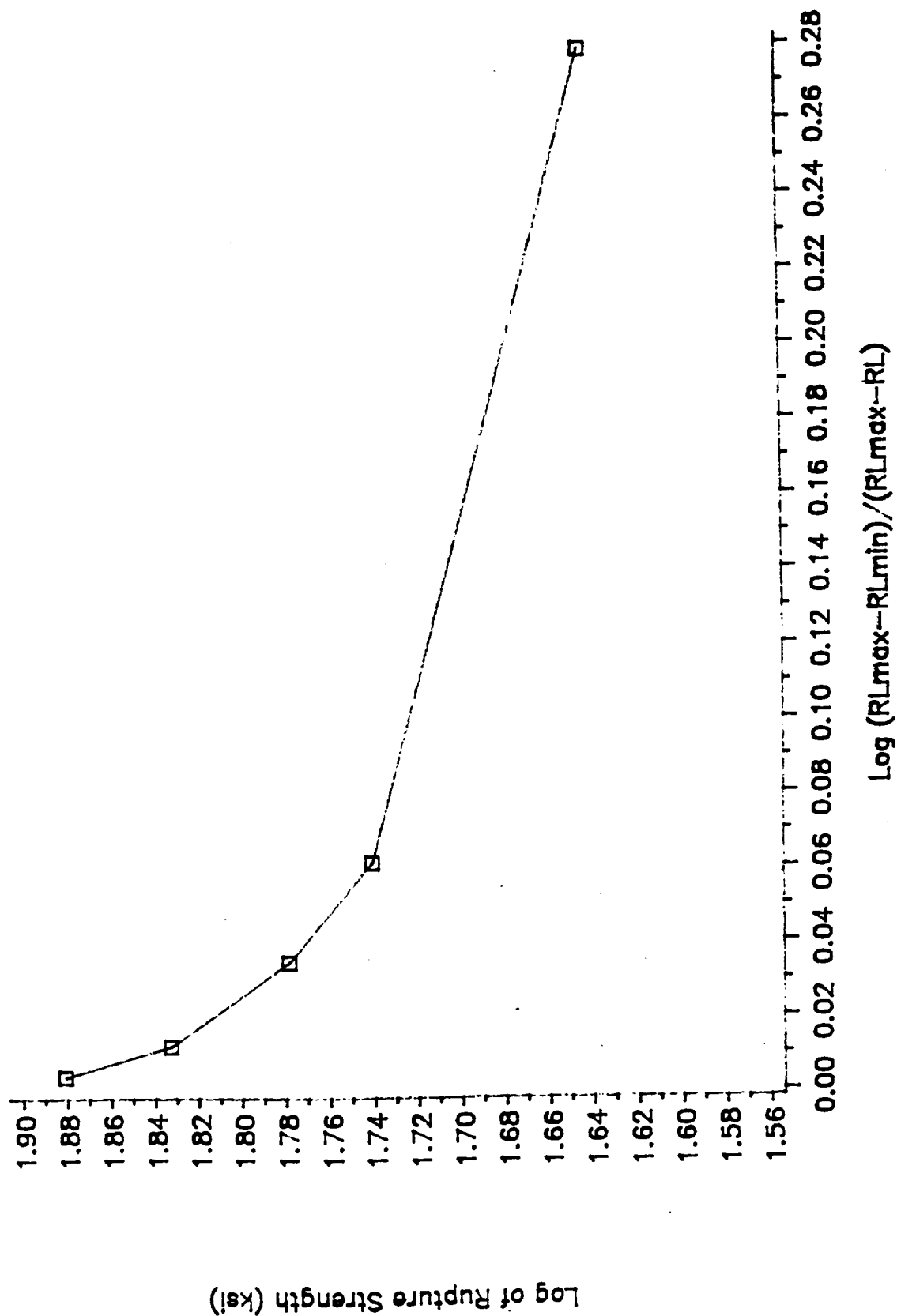
TEST TEMP. = 1300 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



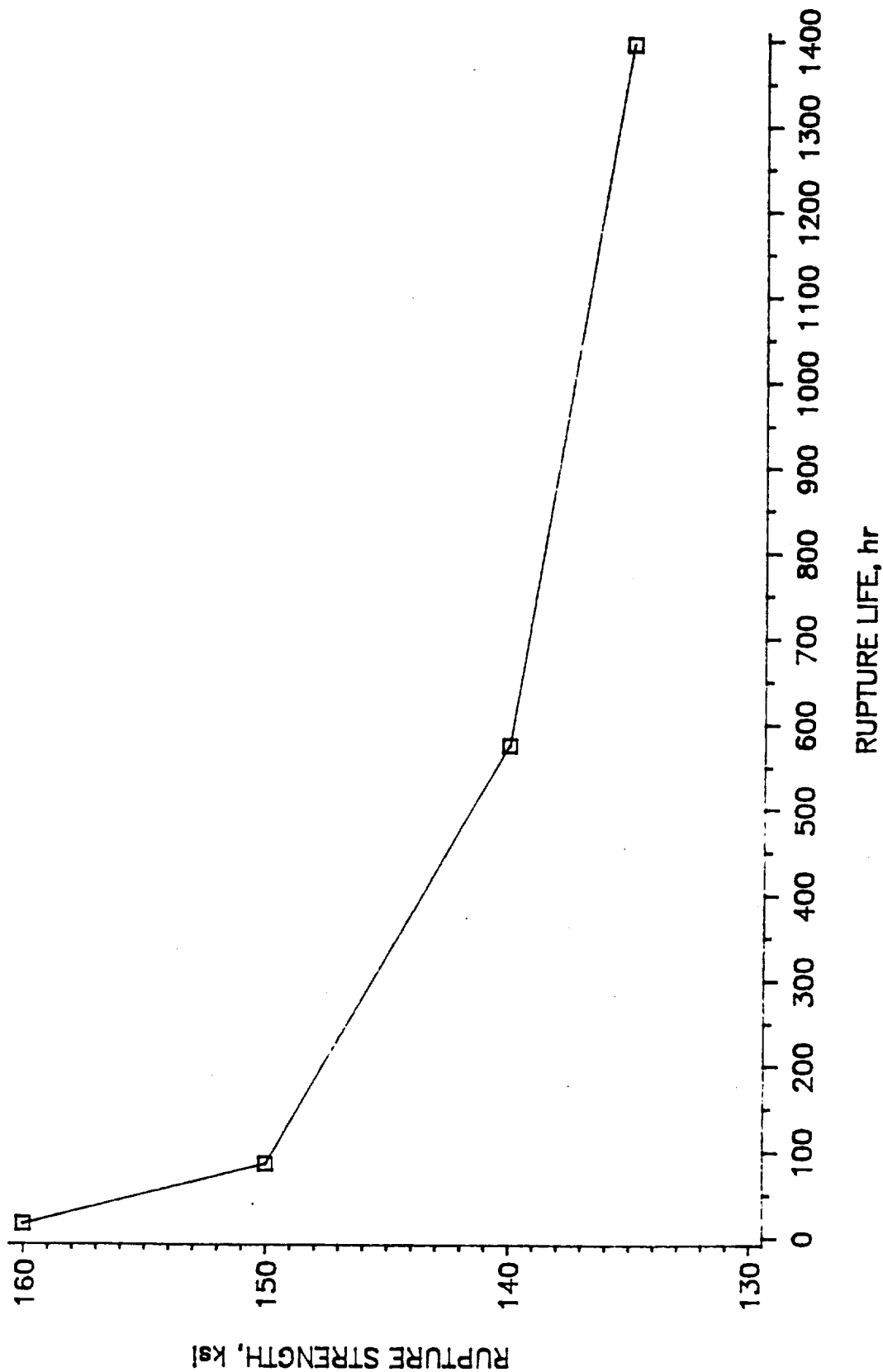
TEST TEMP. = 1300 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



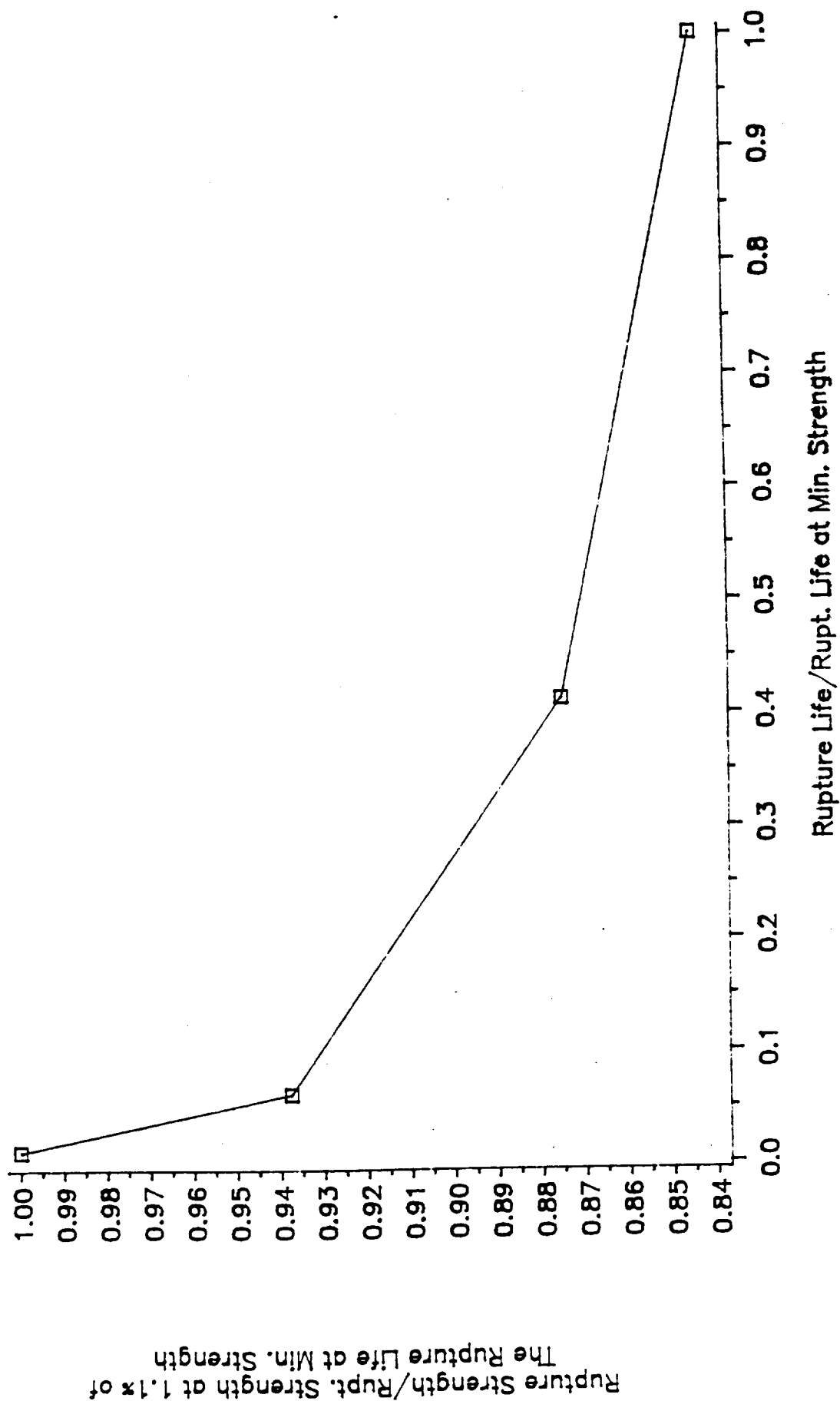
TEST TEMP. = 1000 F
NOTCHED SPECIMEN $K_t=2.3$
ANNLD AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



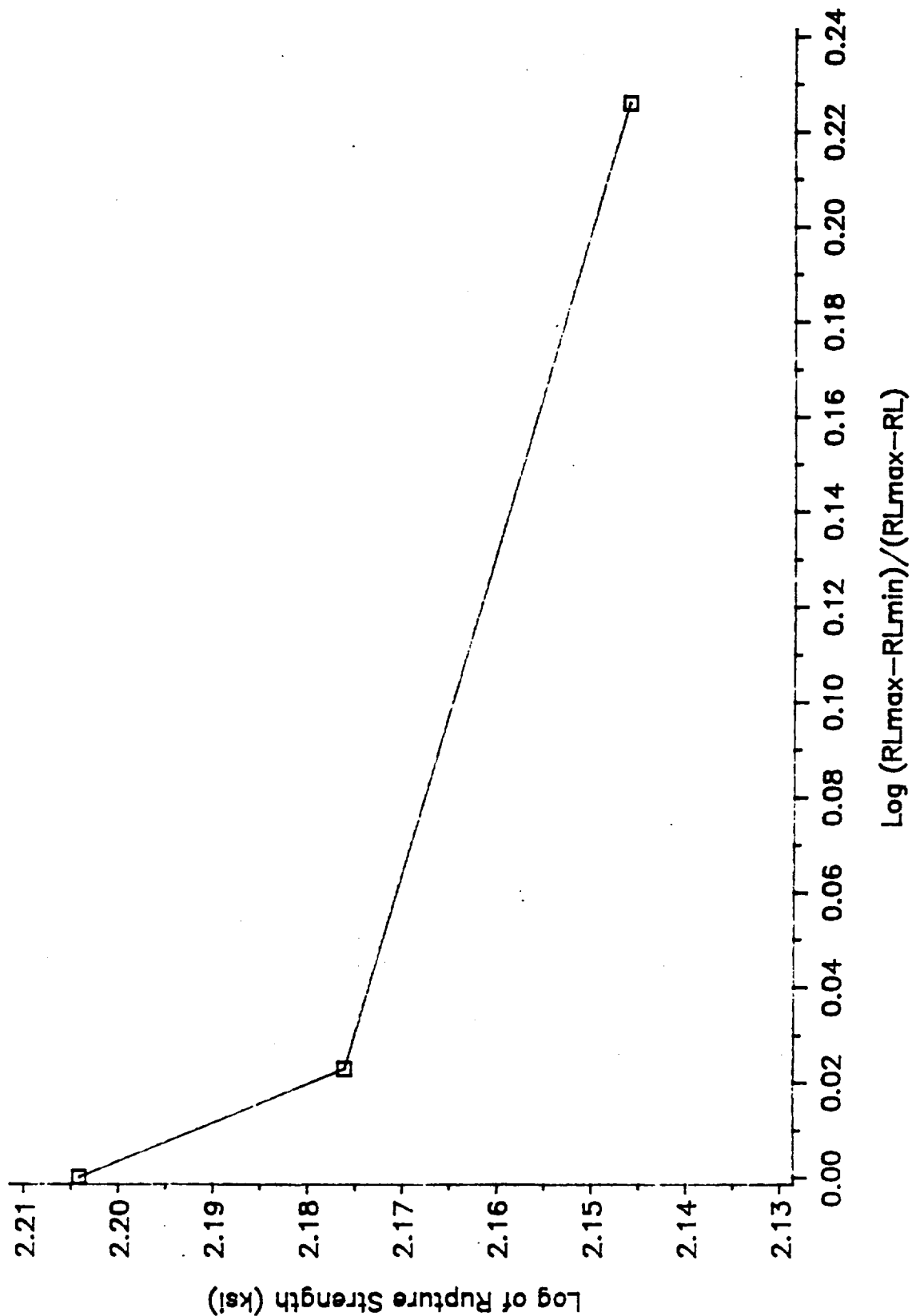
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



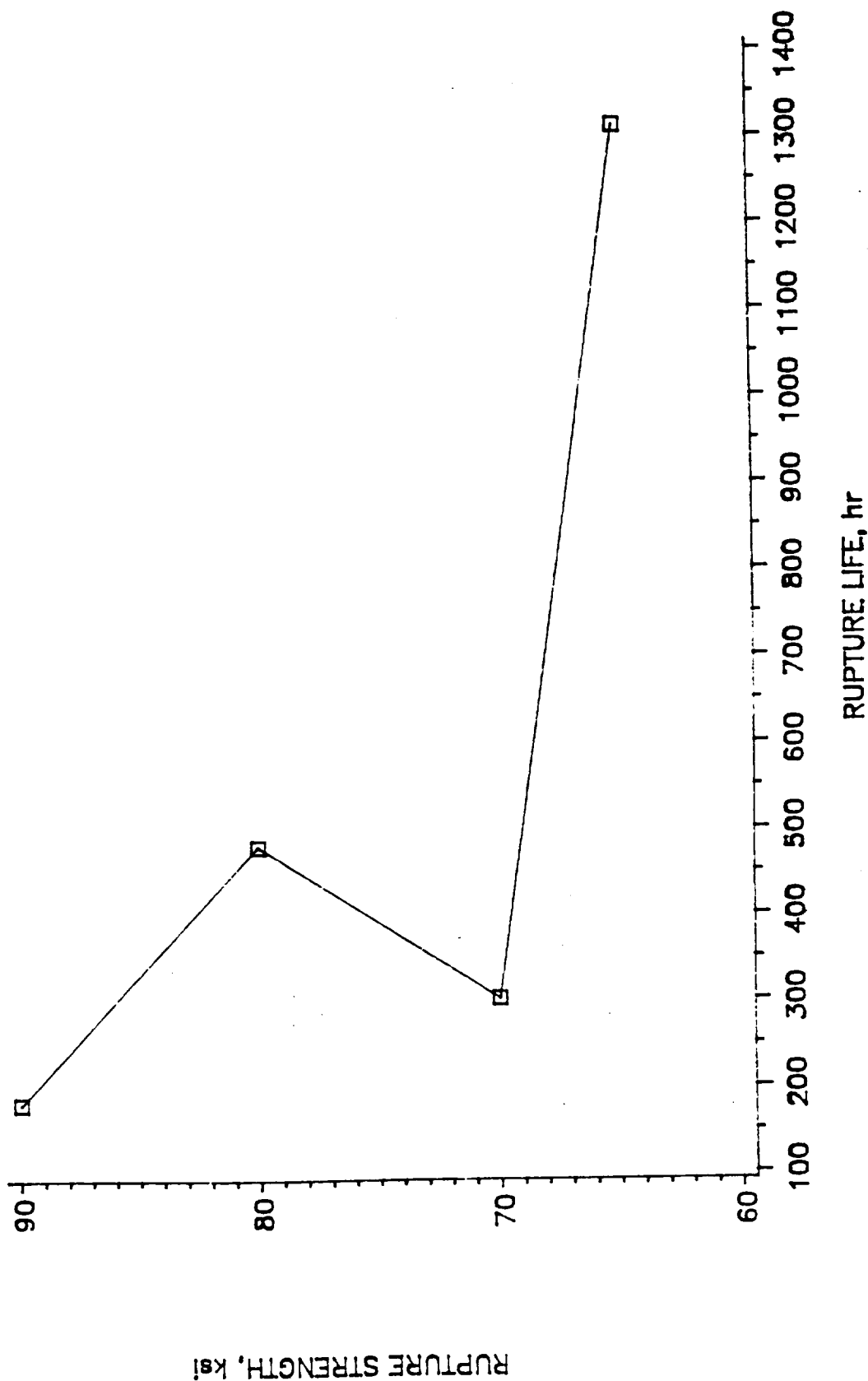
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



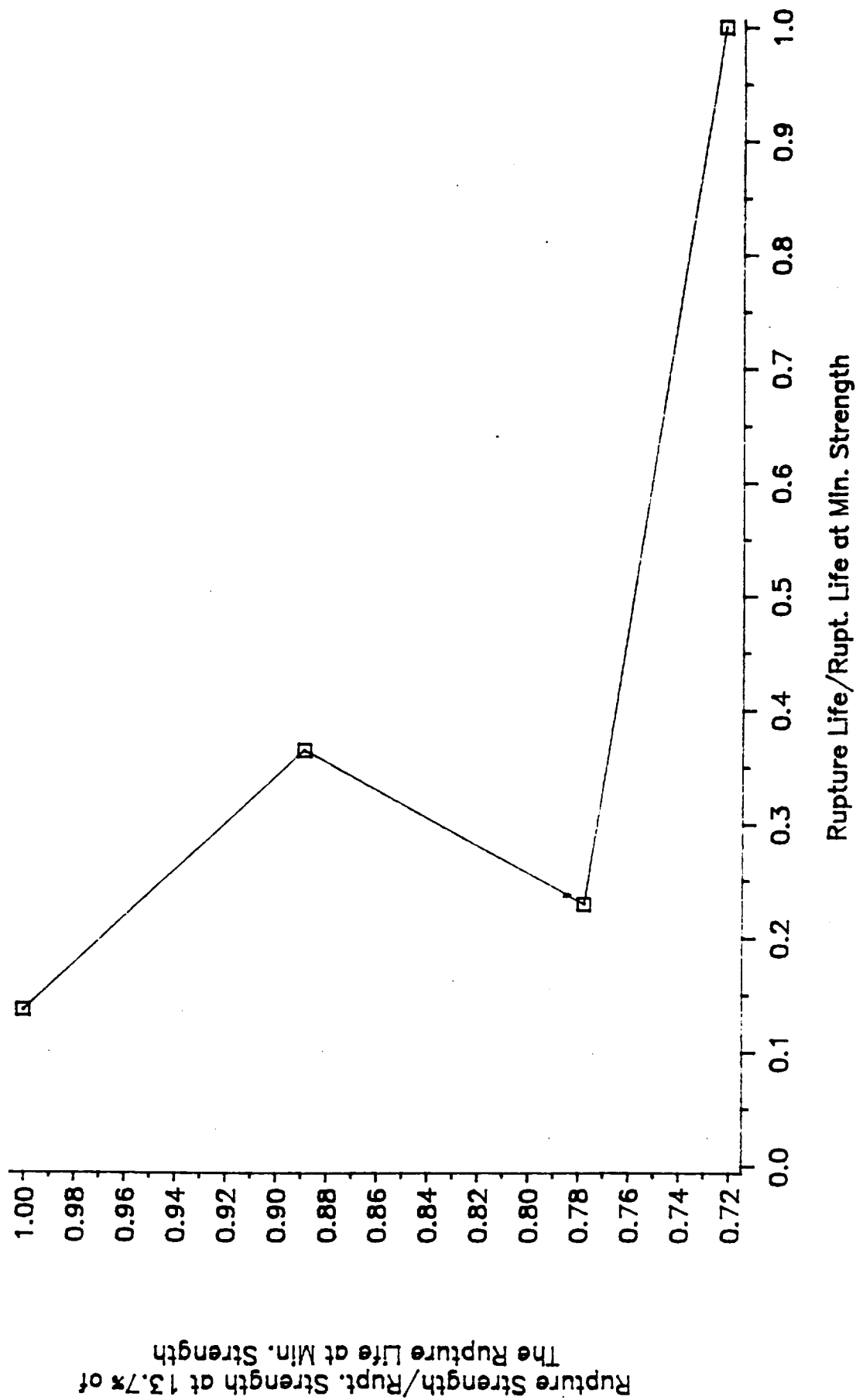
TEST TEMP. = 1200 F
NOTCHED SPECIMEN $Kt=2.3$
ANNILD AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



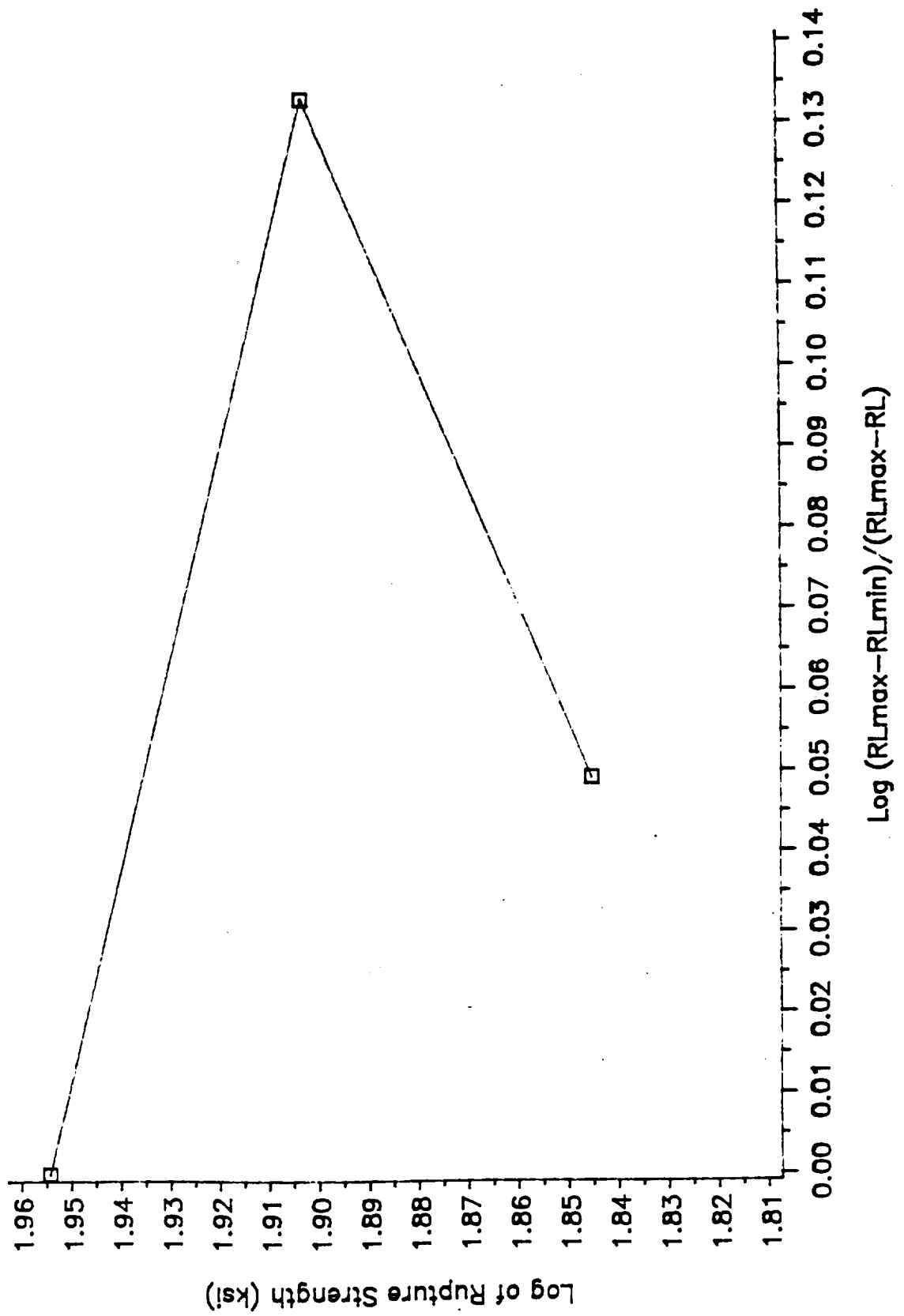
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



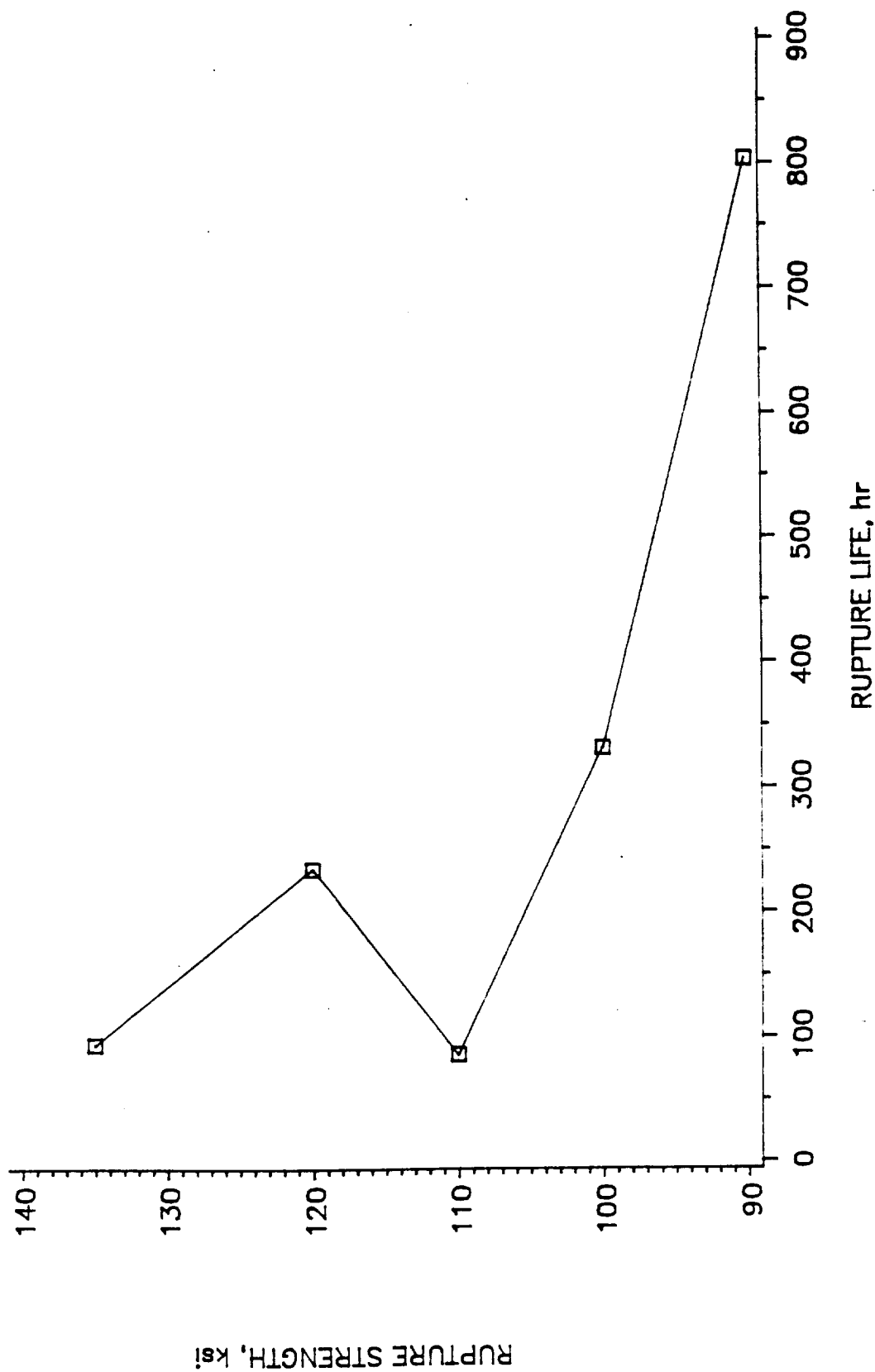
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



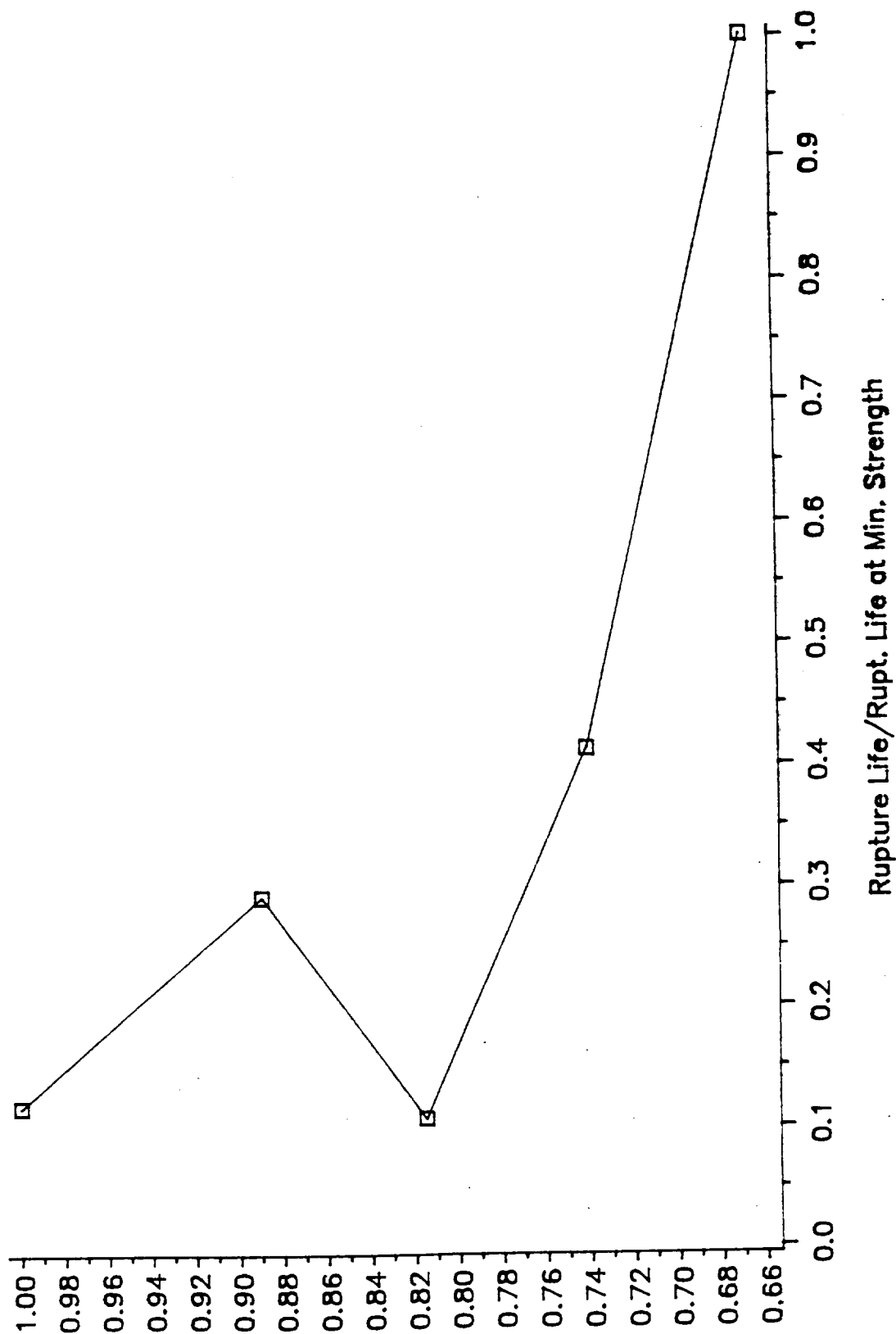
TEST TEMP. = 1000 F
NOTCHED SPECIMEN $K_t=6.0$
COLD WKD 20% & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



TEST TEMP. = 1000 F

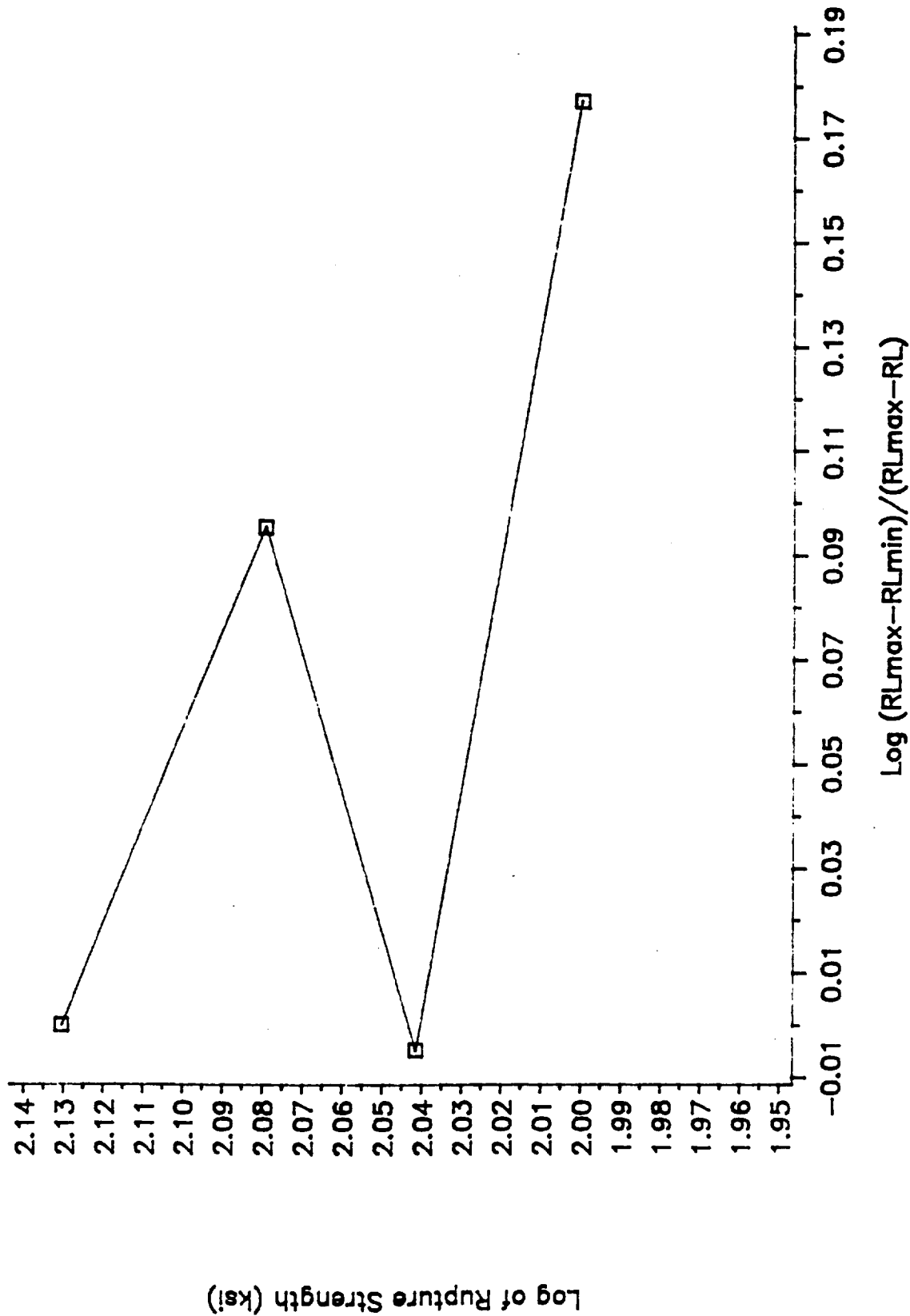
EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



Rupture Strength/Rupt. Strength at 11.7% of
The Rupture Life at Min. Strength

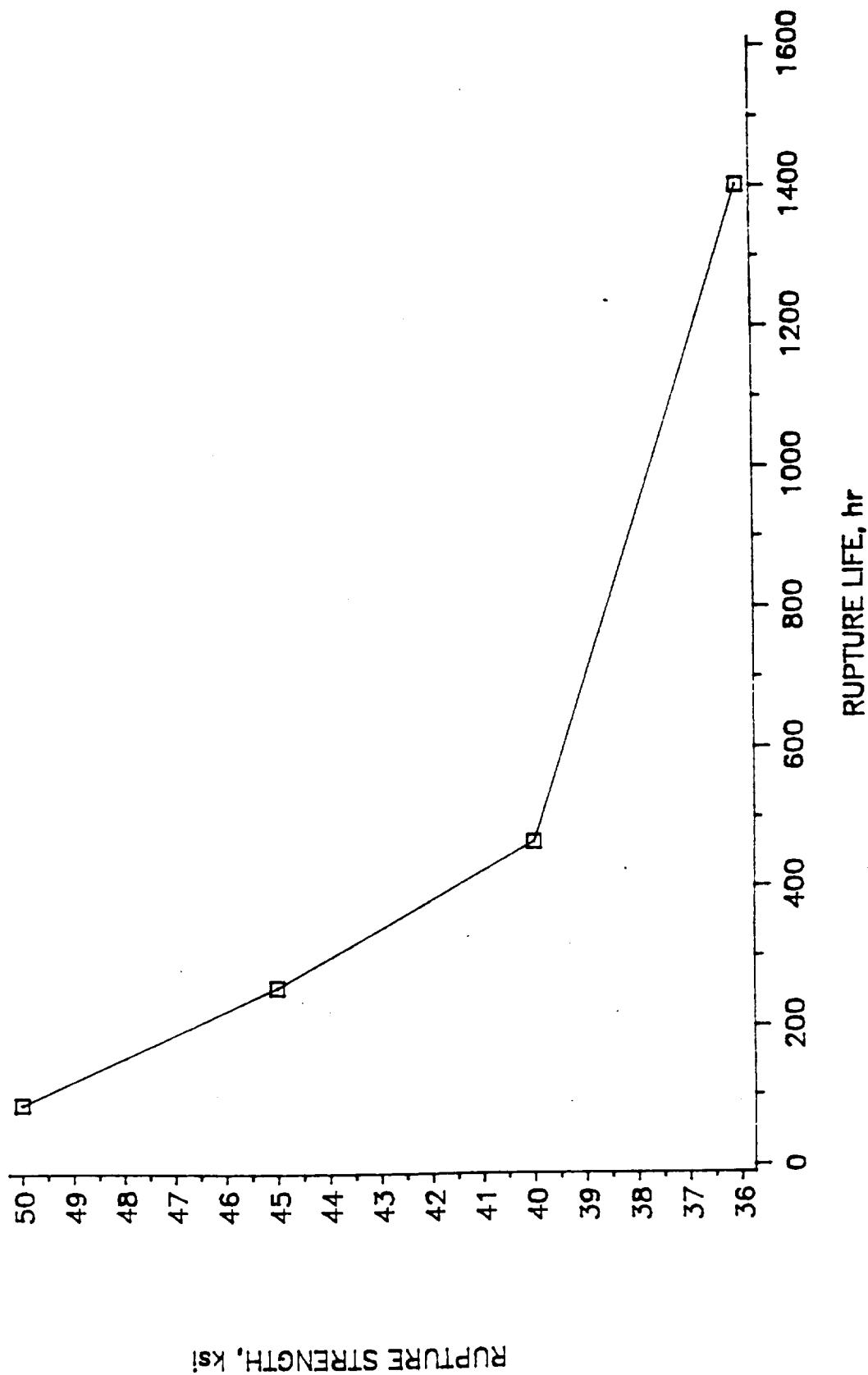
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



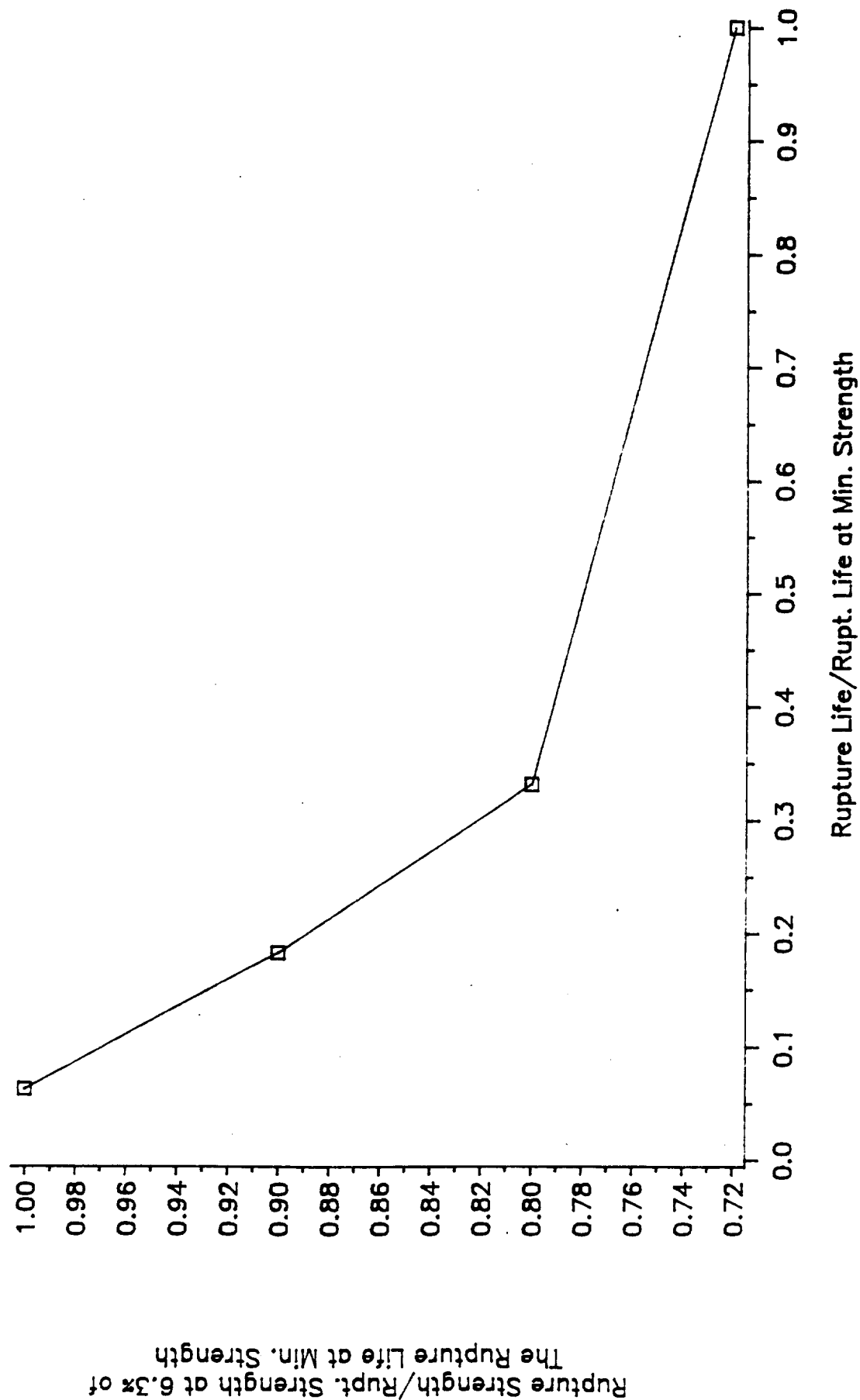
TEST TEMP. = 1200 F
NOTCHED SPECIMEN $K_t=6.0$
COLD WKD 20% & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



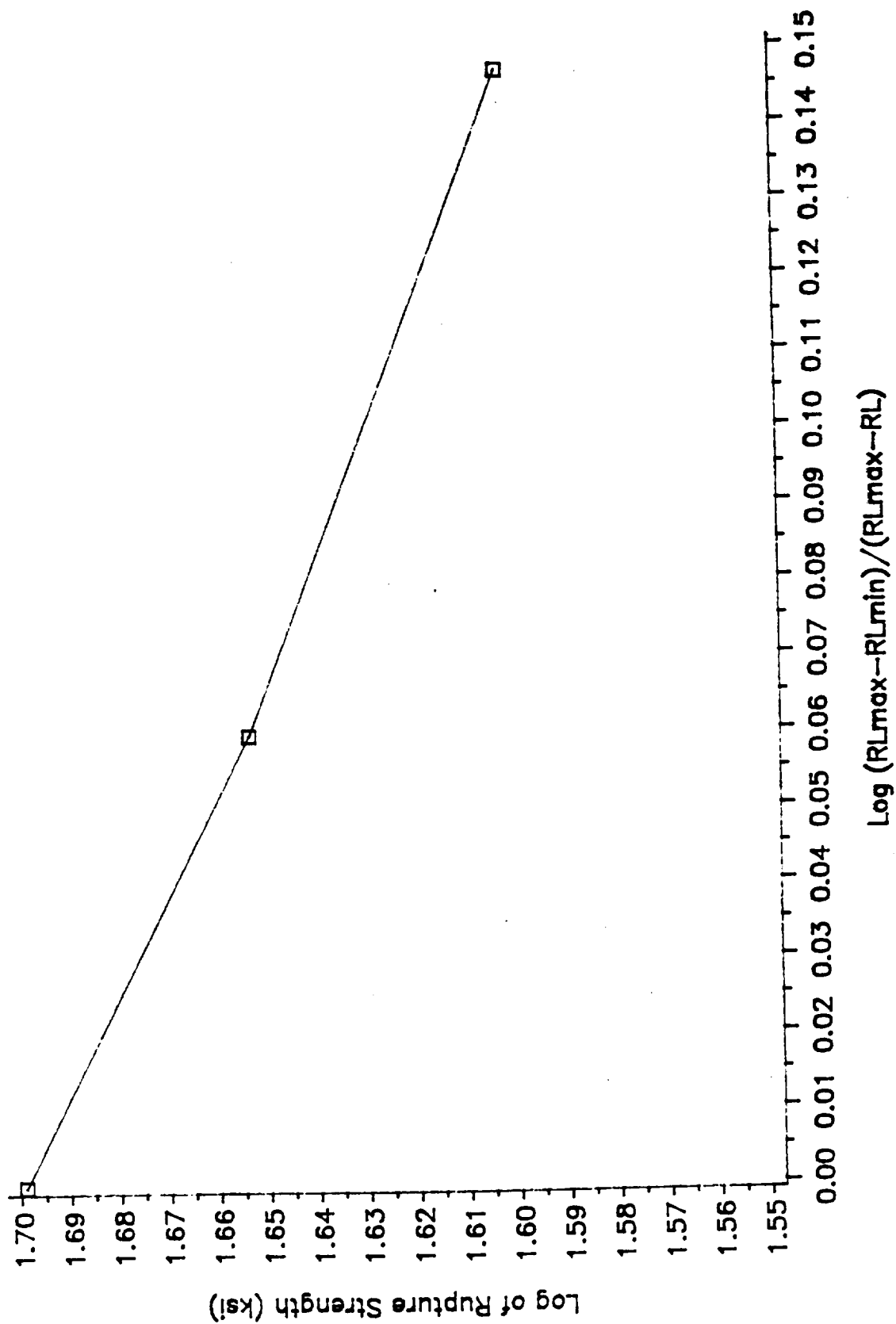
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



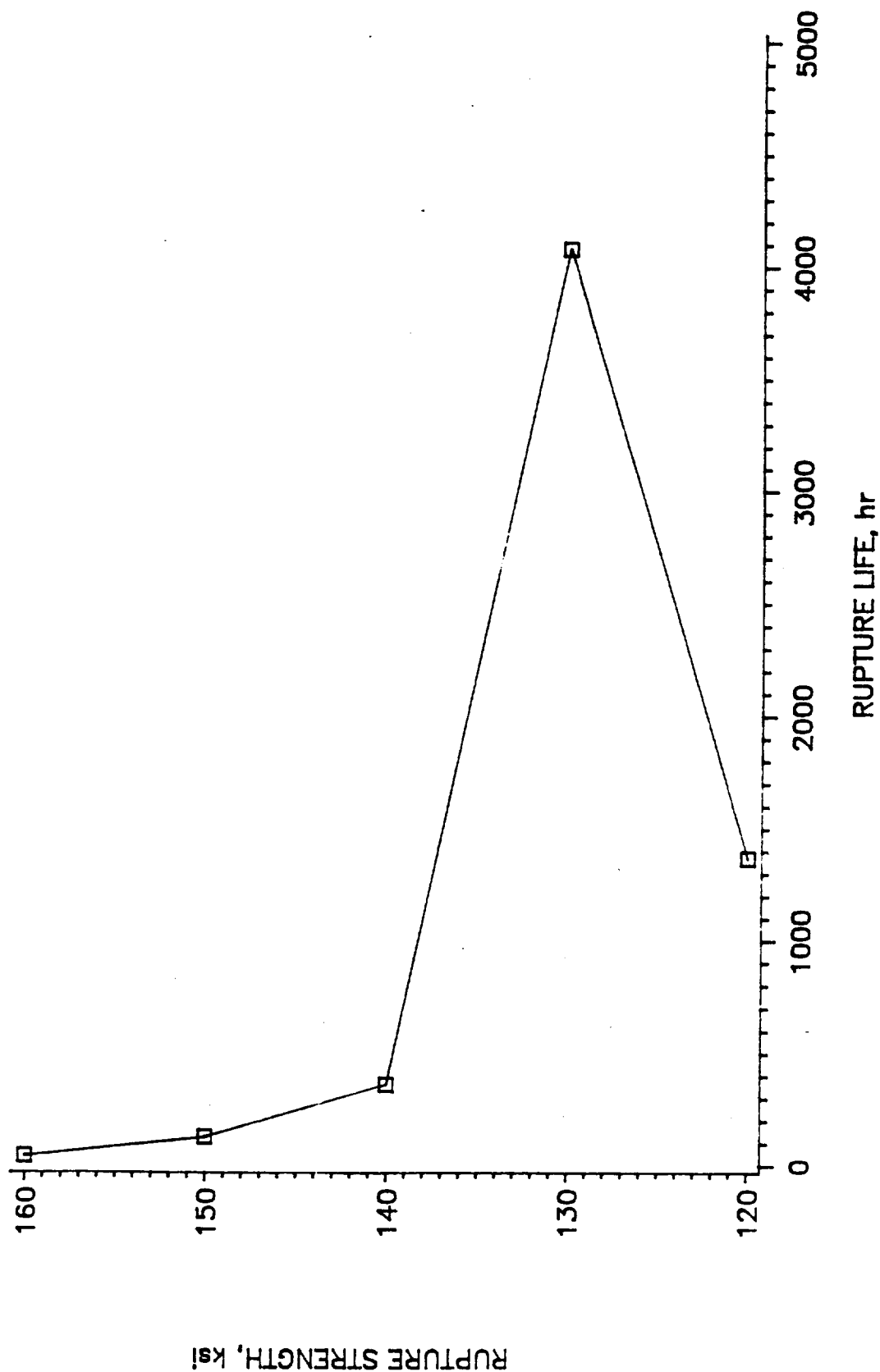
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



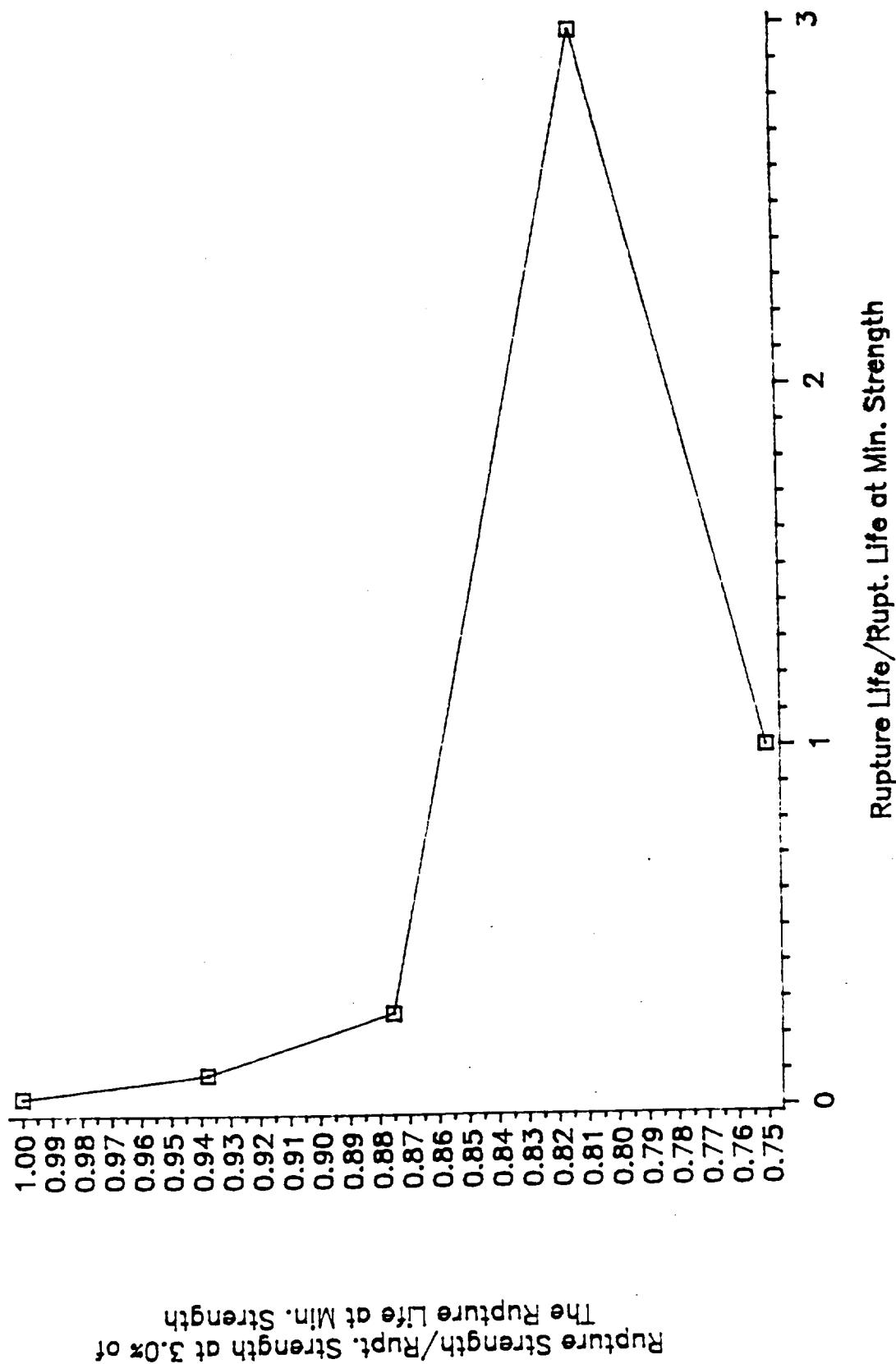
TEST TEMP. = 1000 F
NOTCHED SPECIMEN $K_t=6.0$
ANNEAL AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



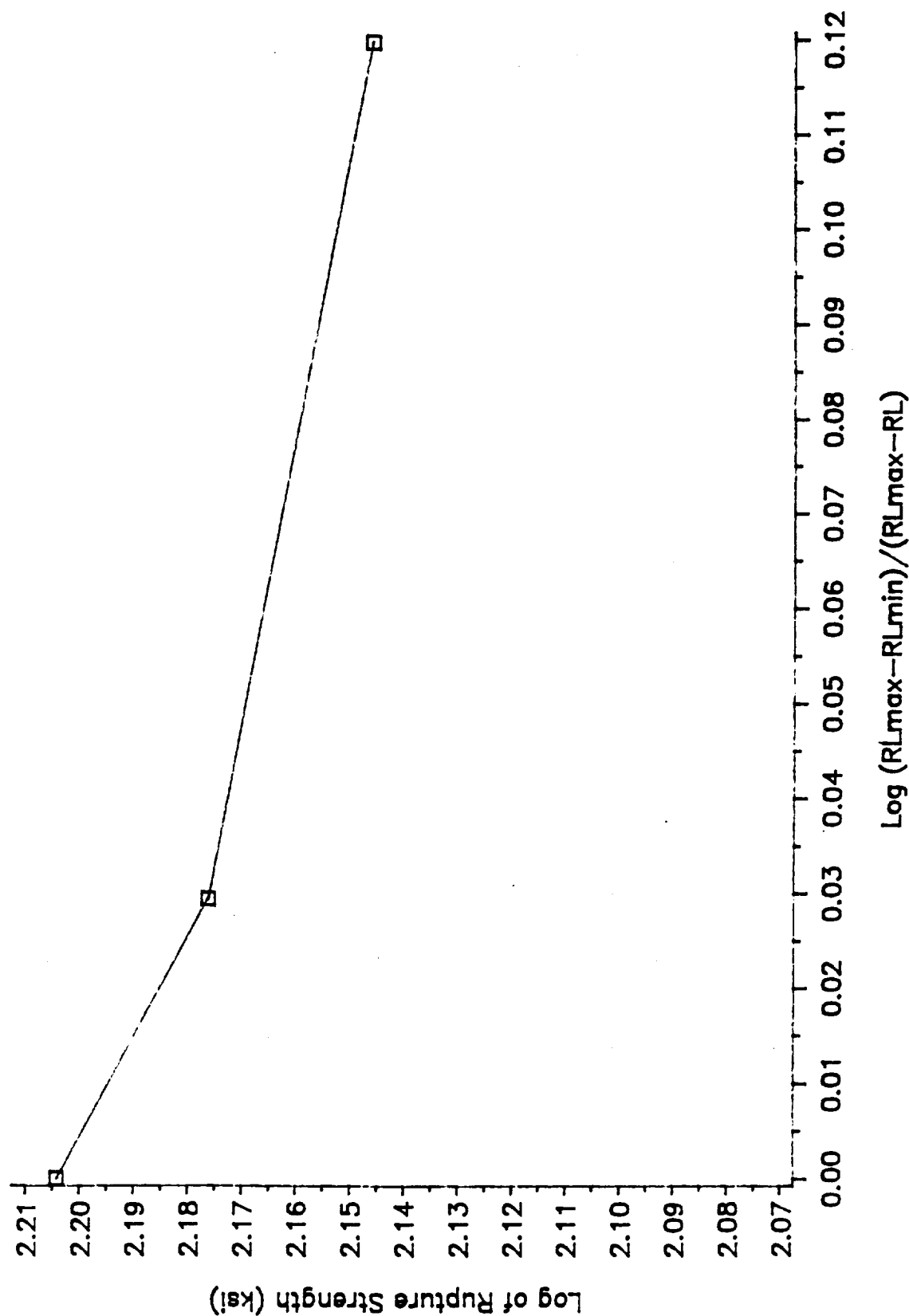
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



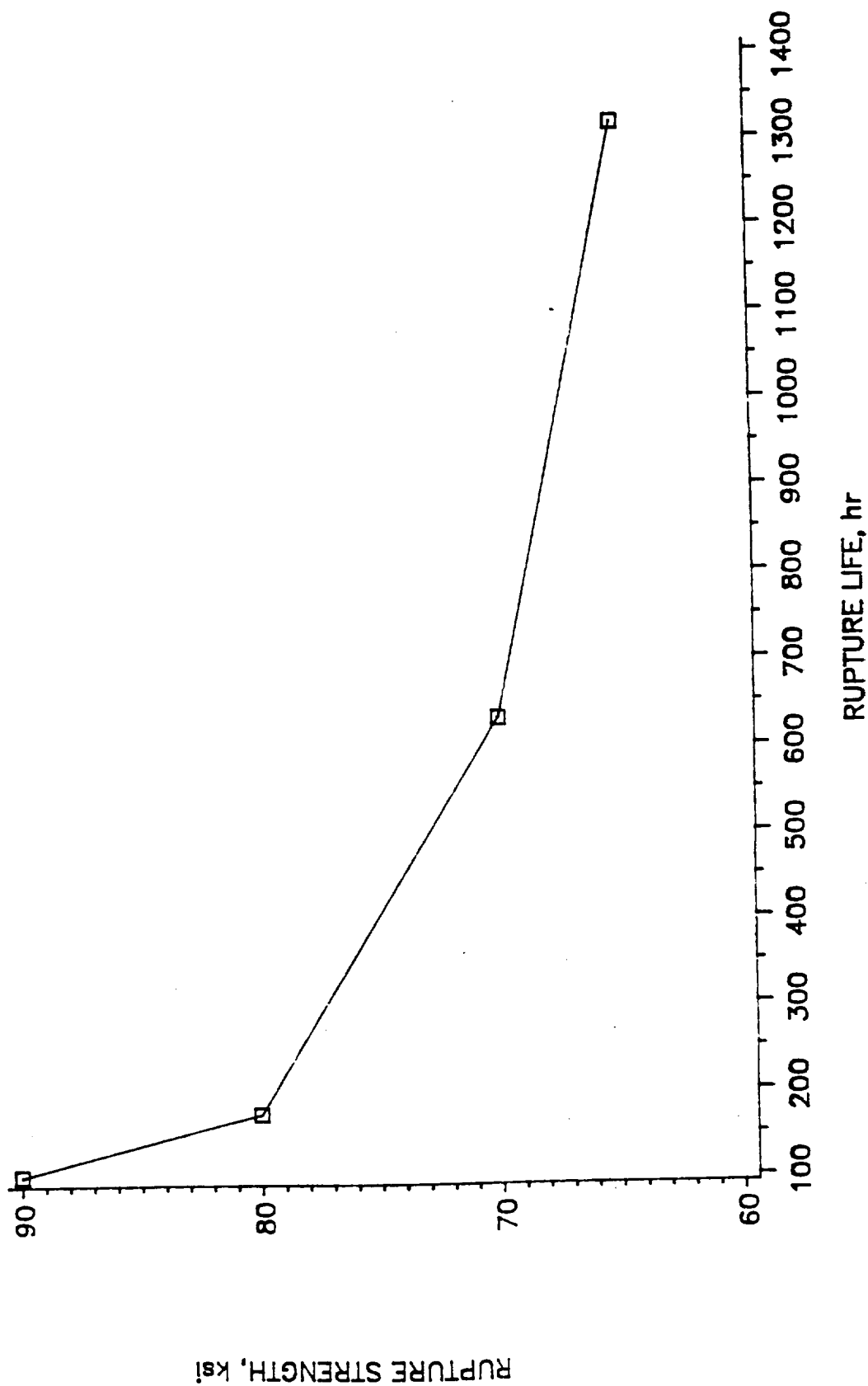
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



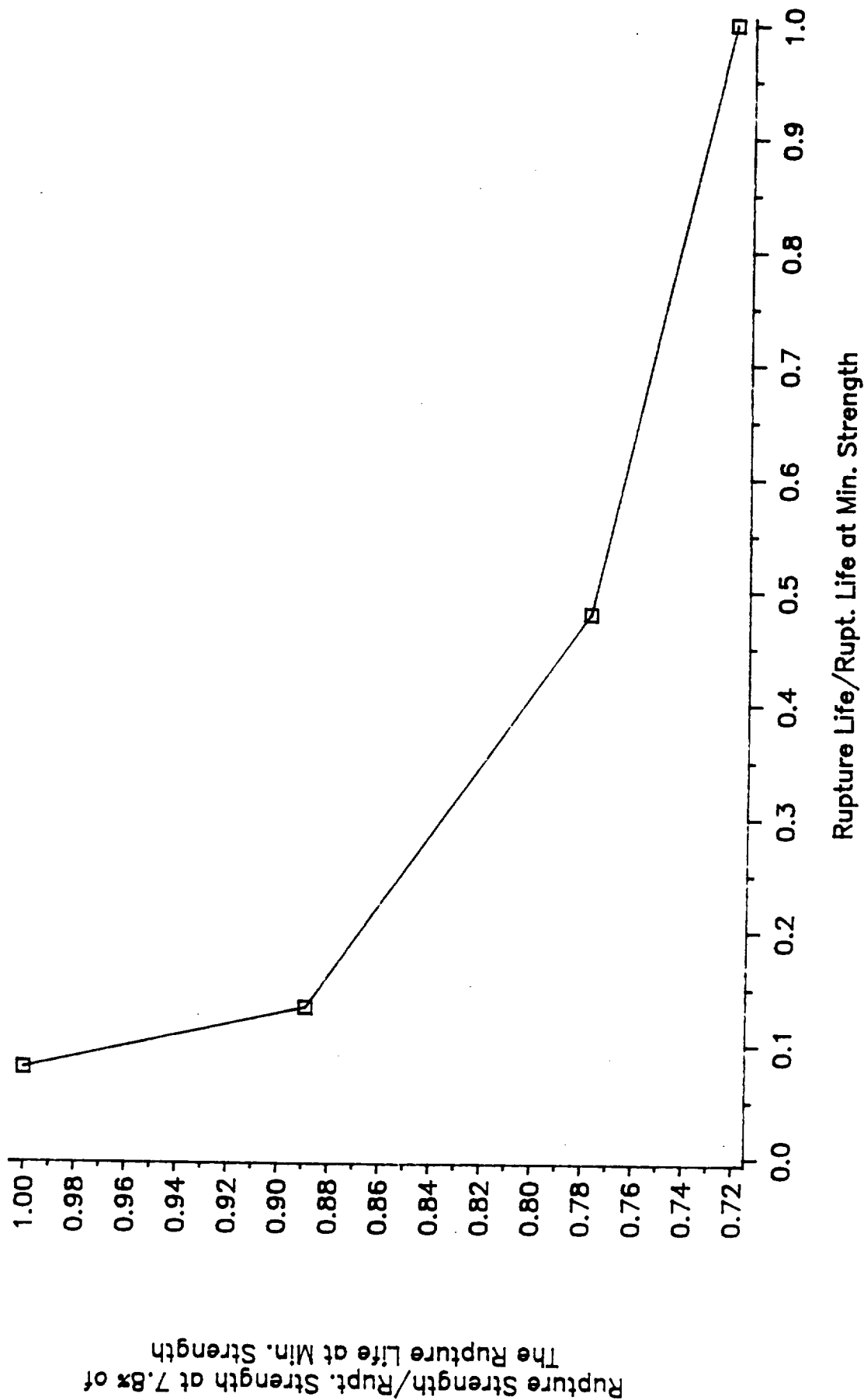
TEST TEMP. = 1200 F
NOTCHED SPECIMEN Kt=6.0
ANNEAL AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



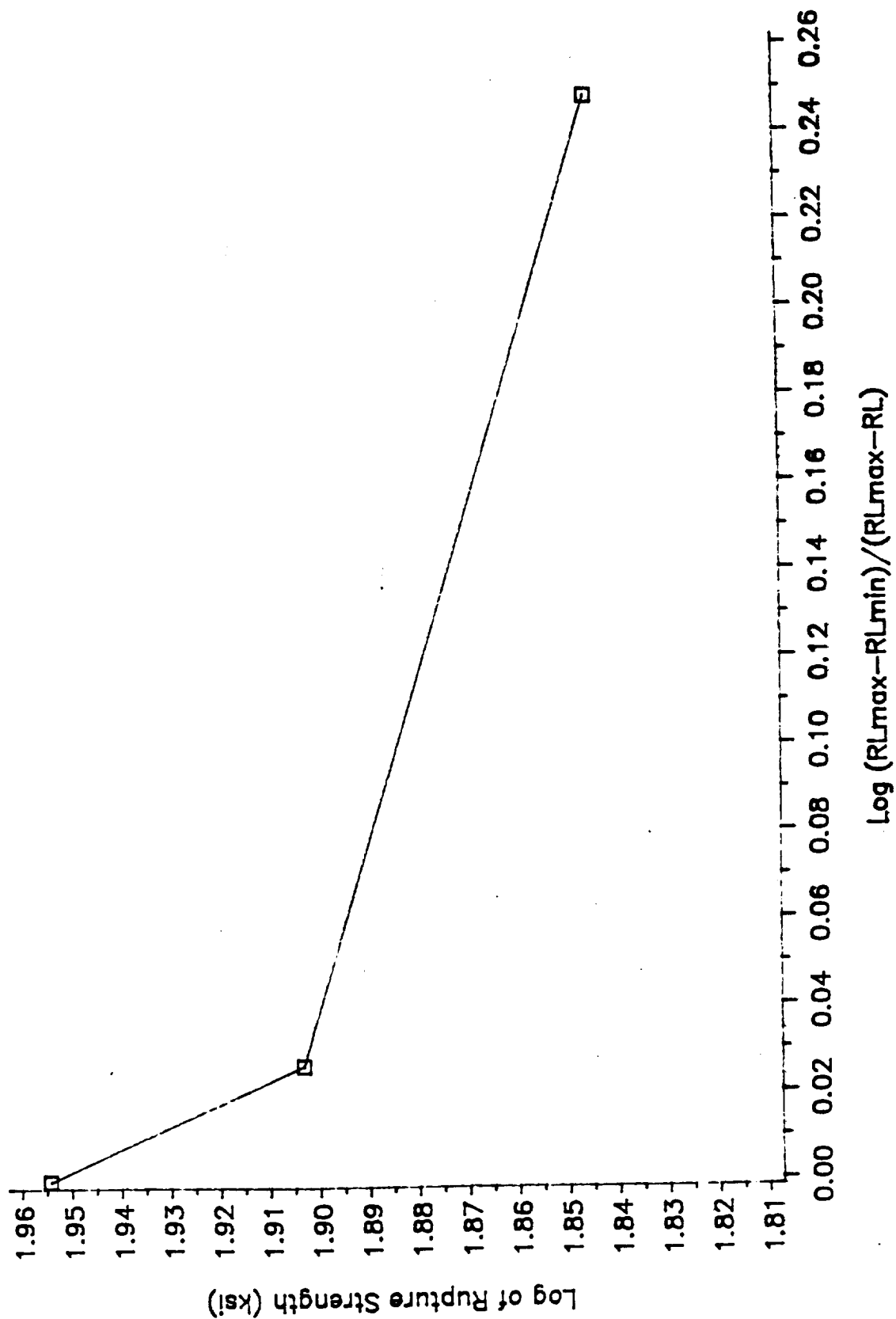
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



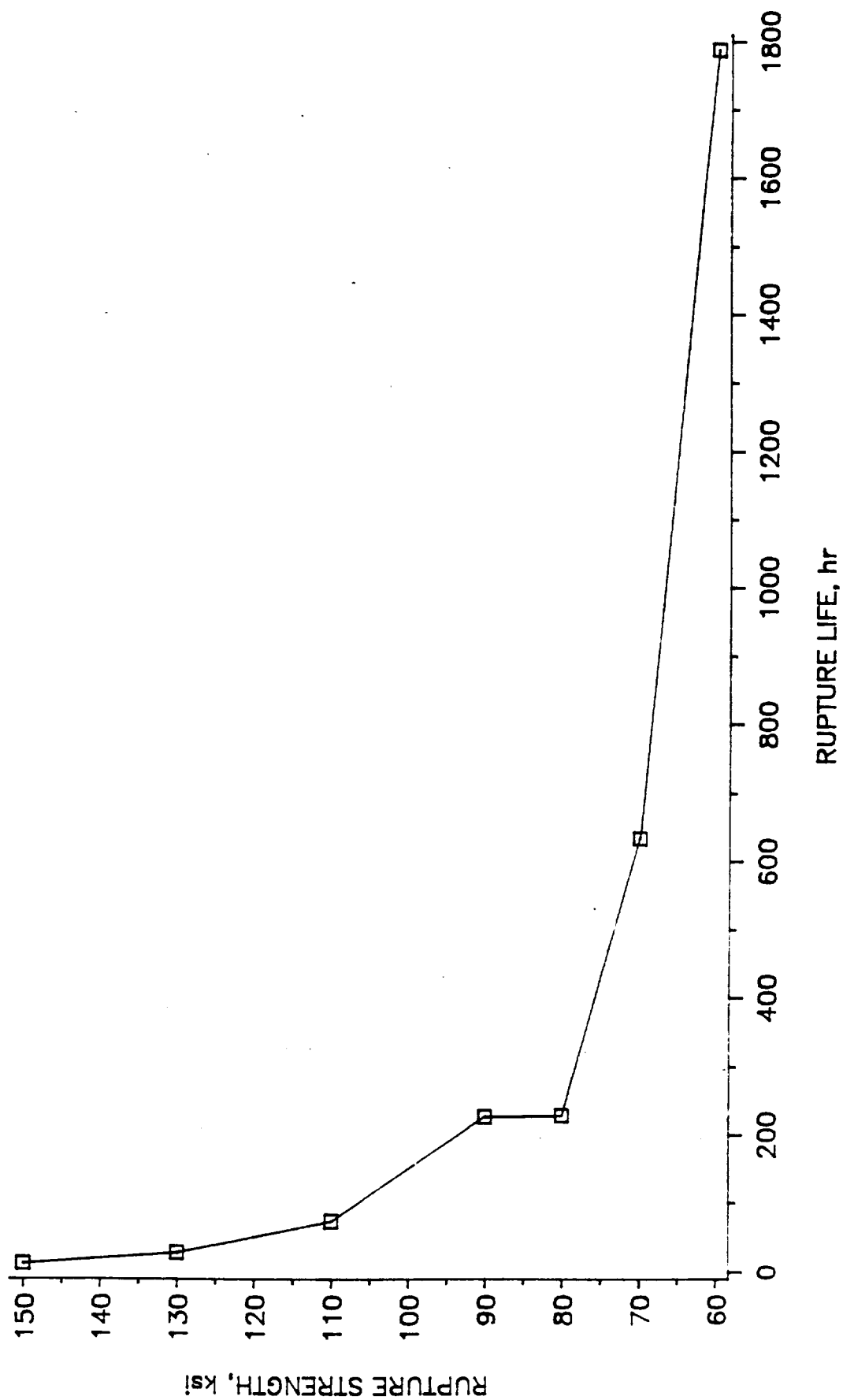
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



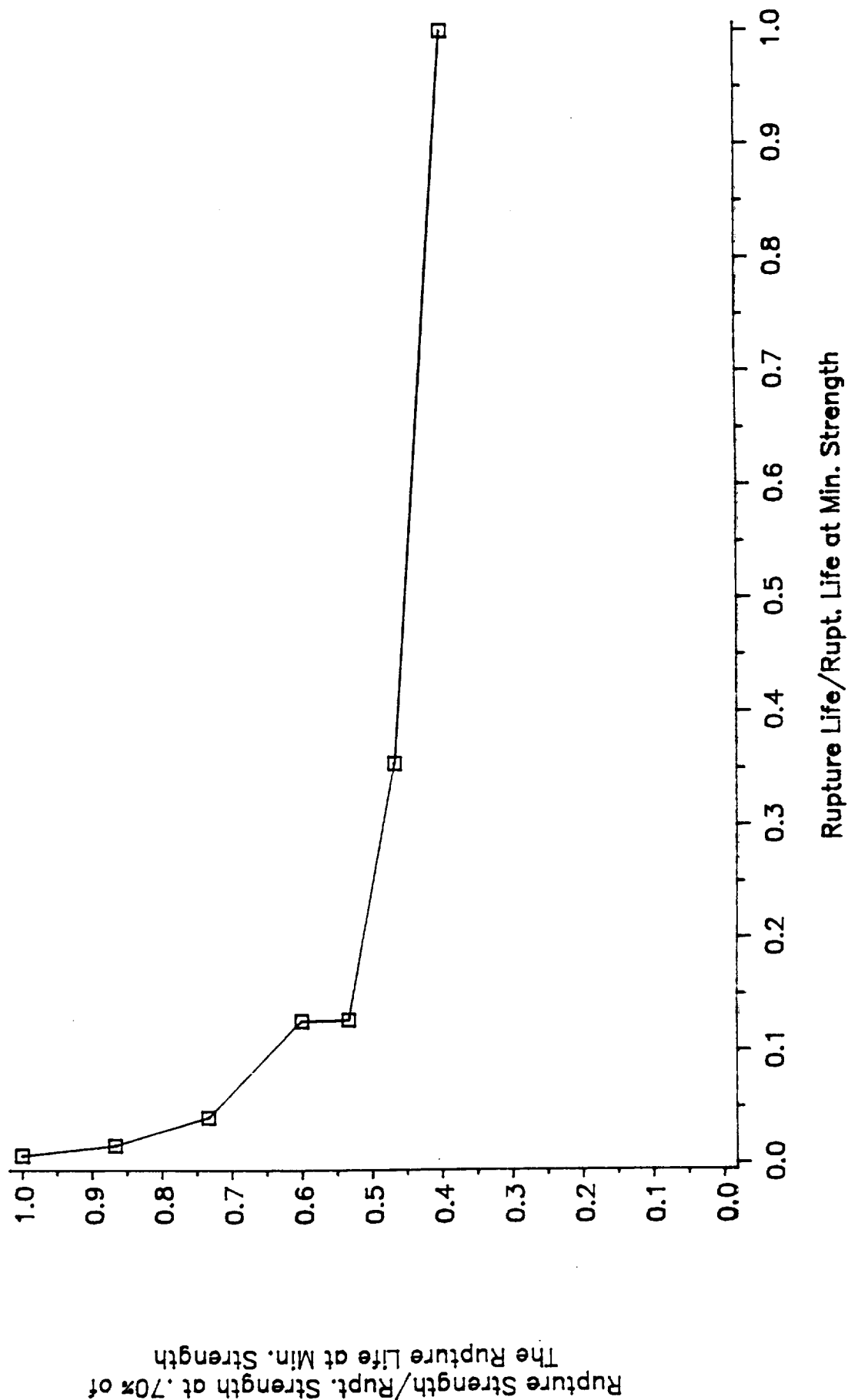
TEST TEMP. = 1000 F
SHARP EDGE-NOTCHED -- Kt>20

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



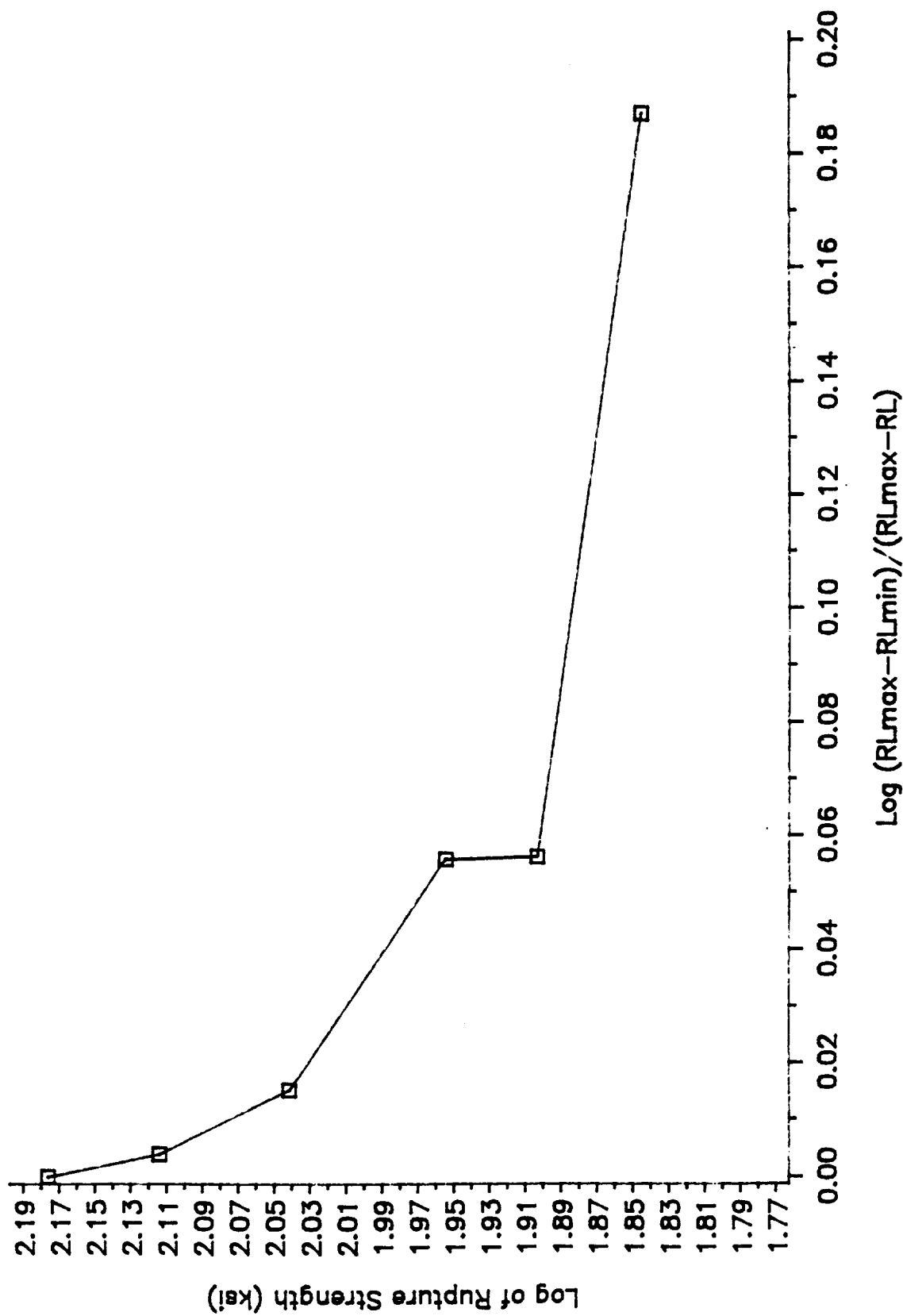
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



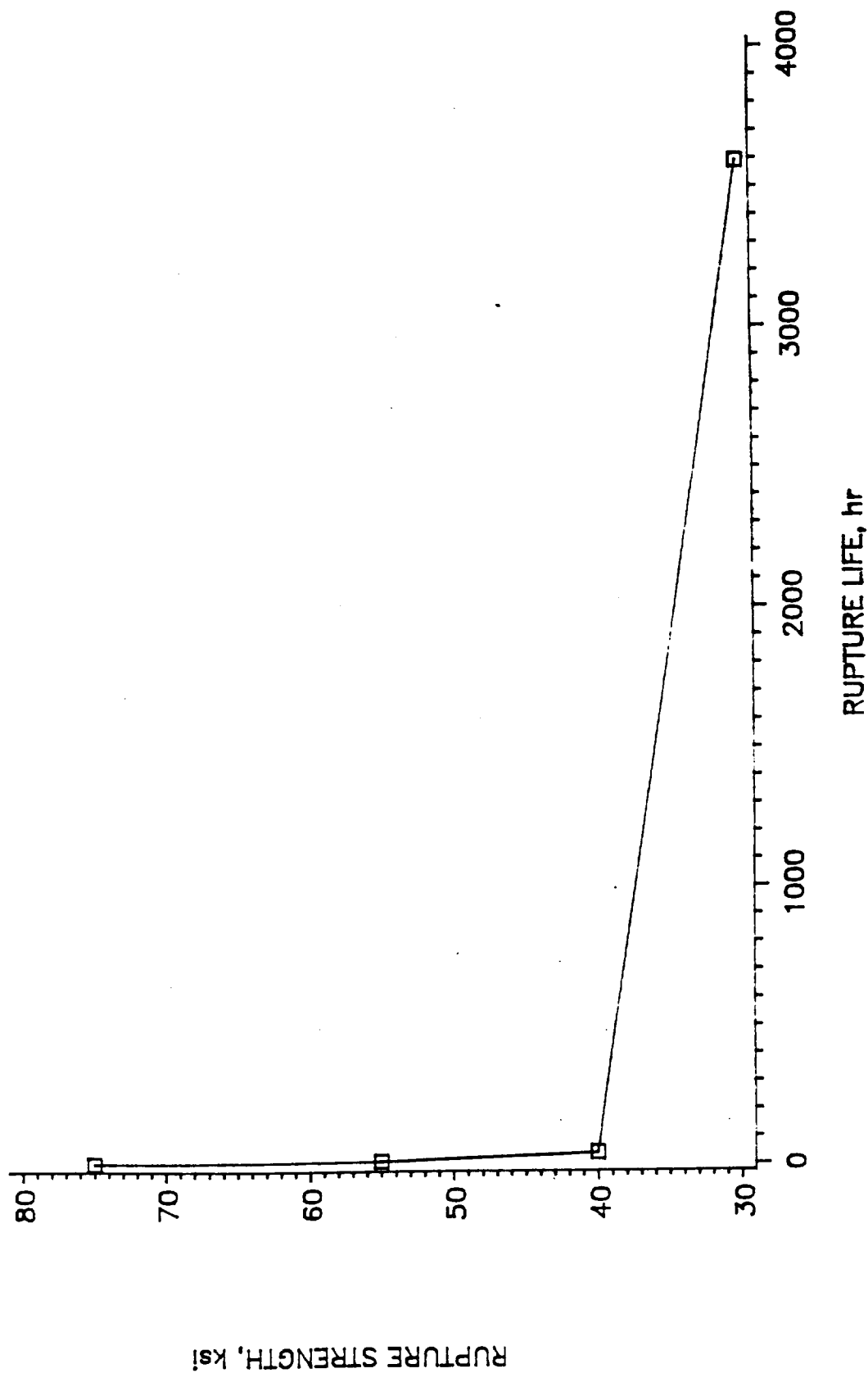
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



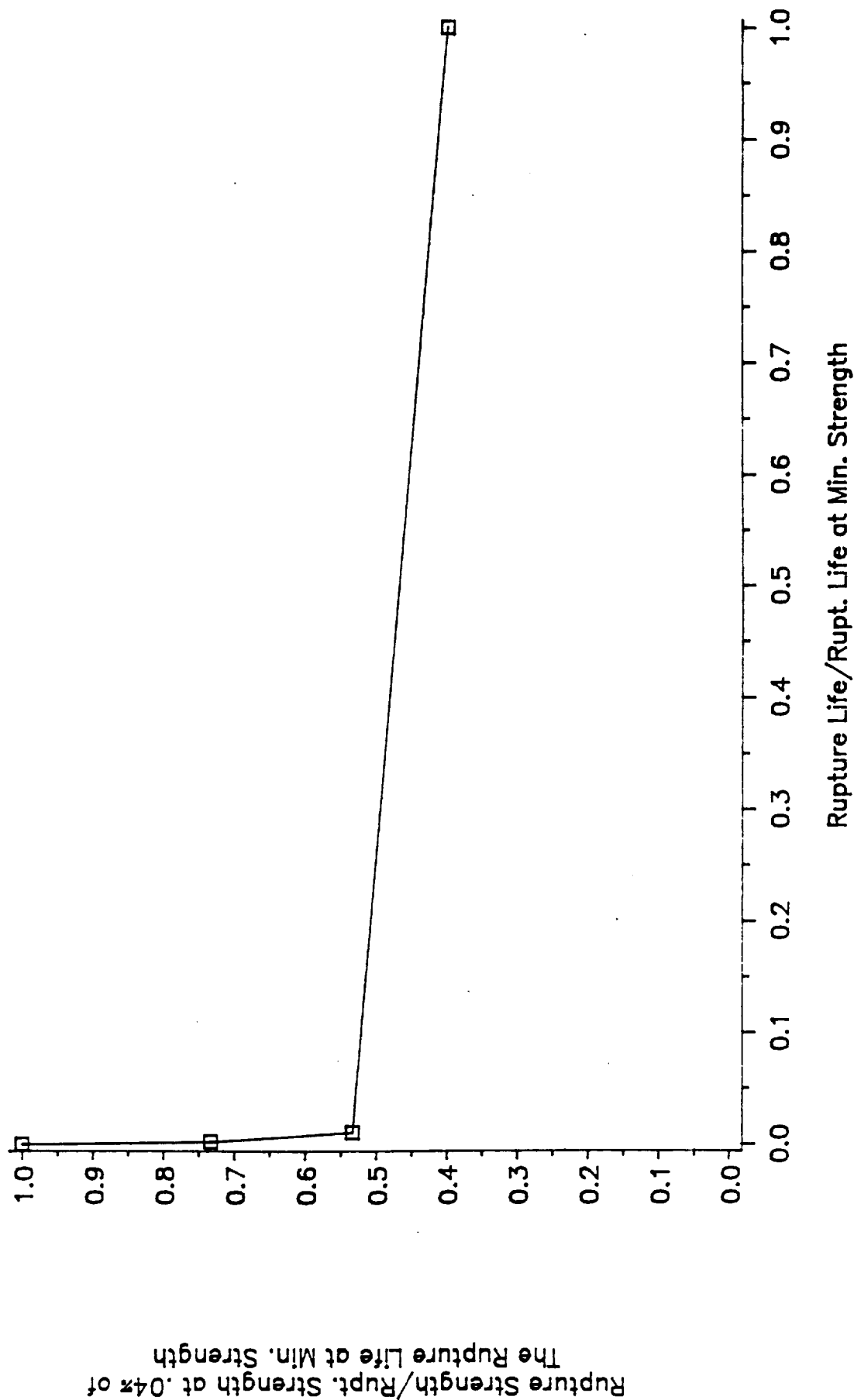
TEST TEMP. = 1200 F
NOTCHED Kt > 20
COLD WKD 20% & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



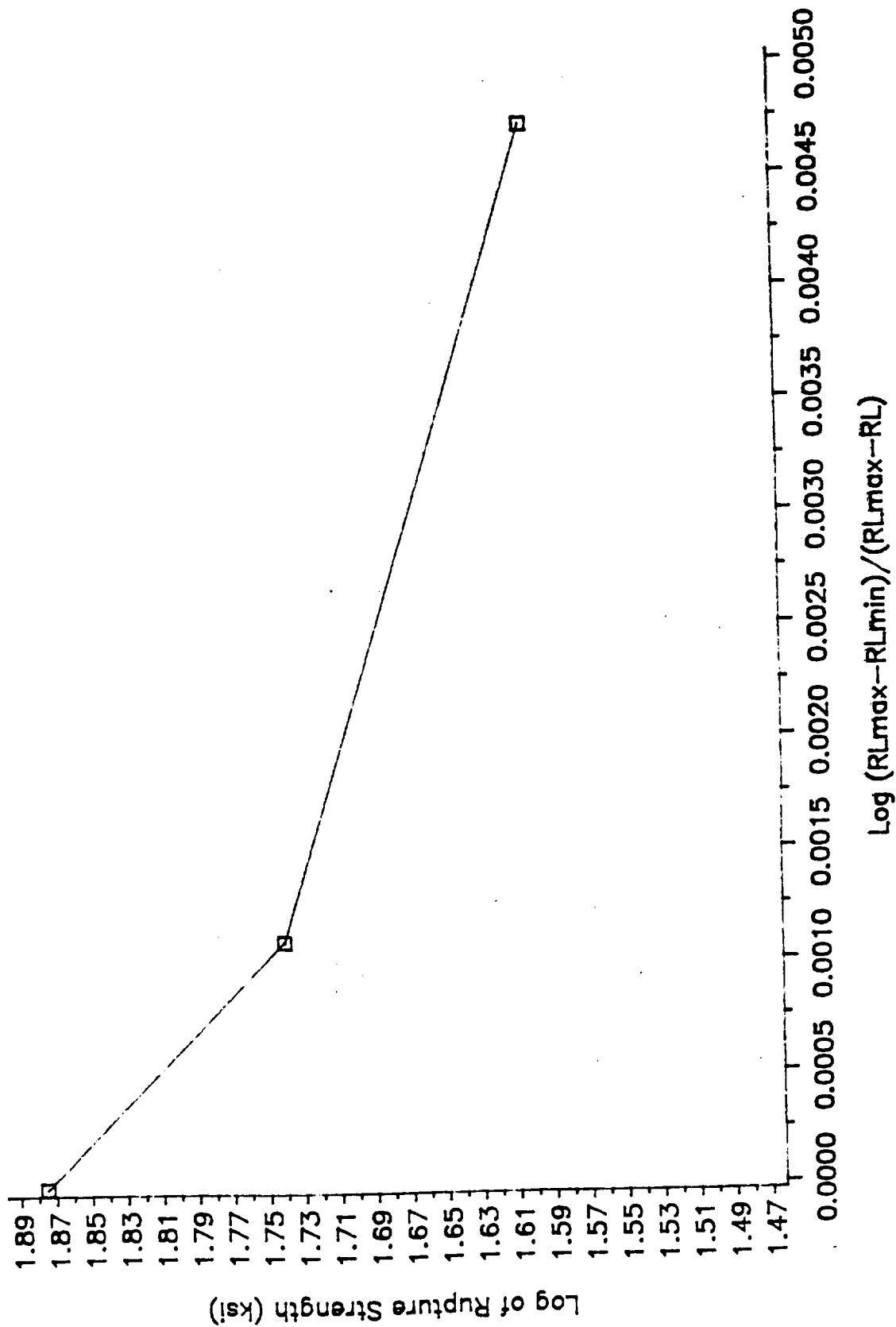
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



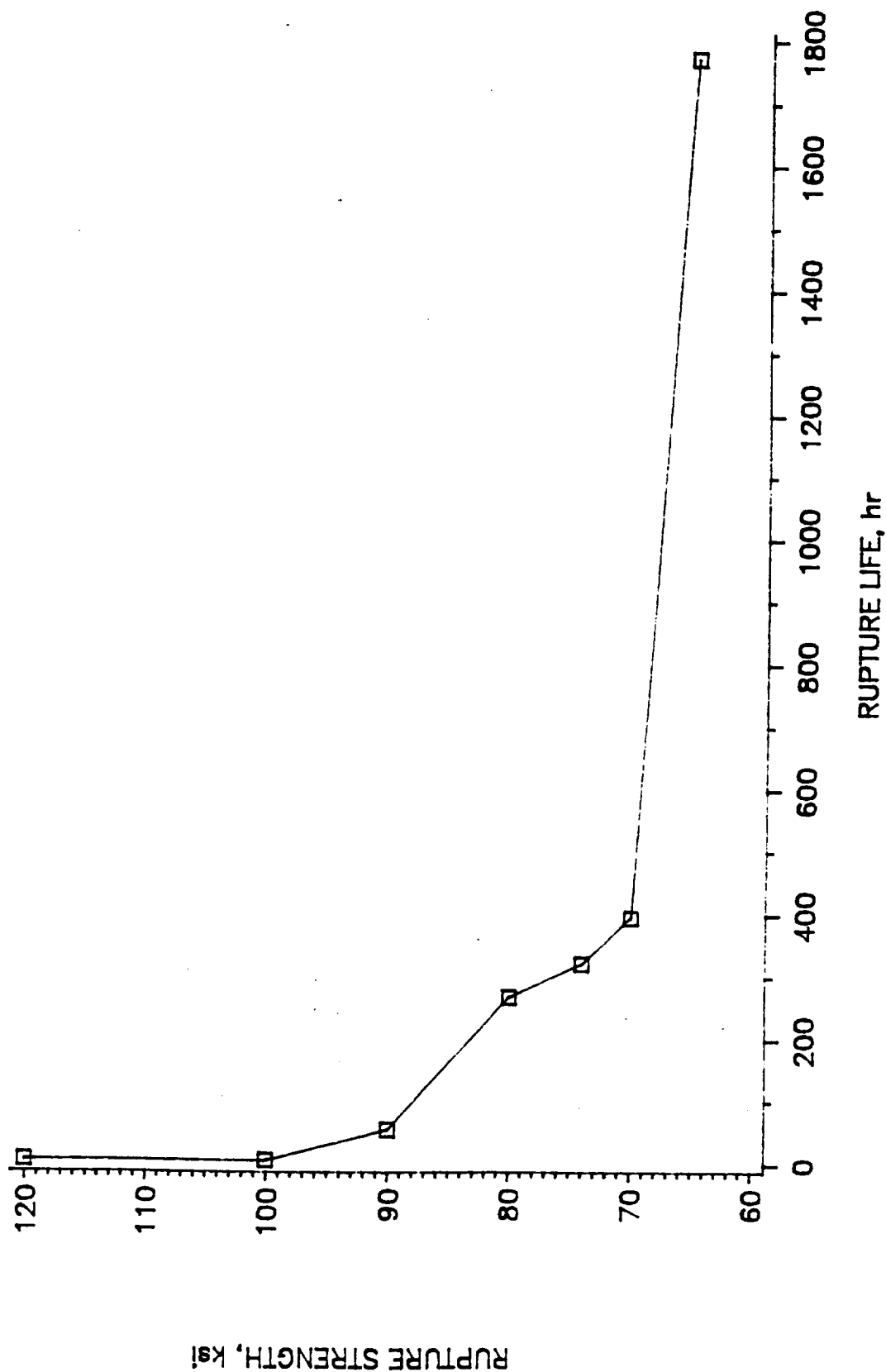
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



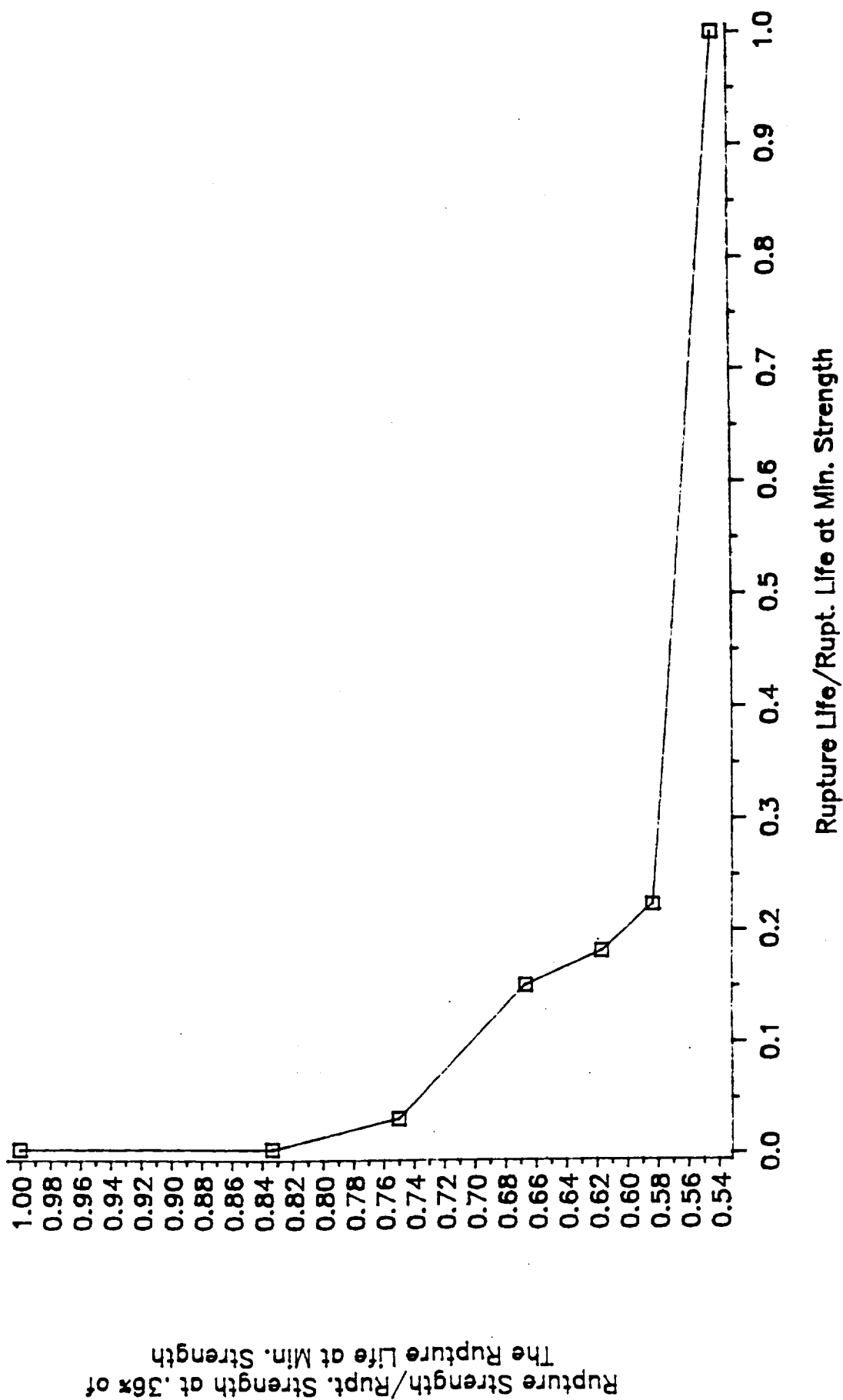
TEST TEMP. = 1000 F
NOTCHED Kt > 20
ANNLD AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



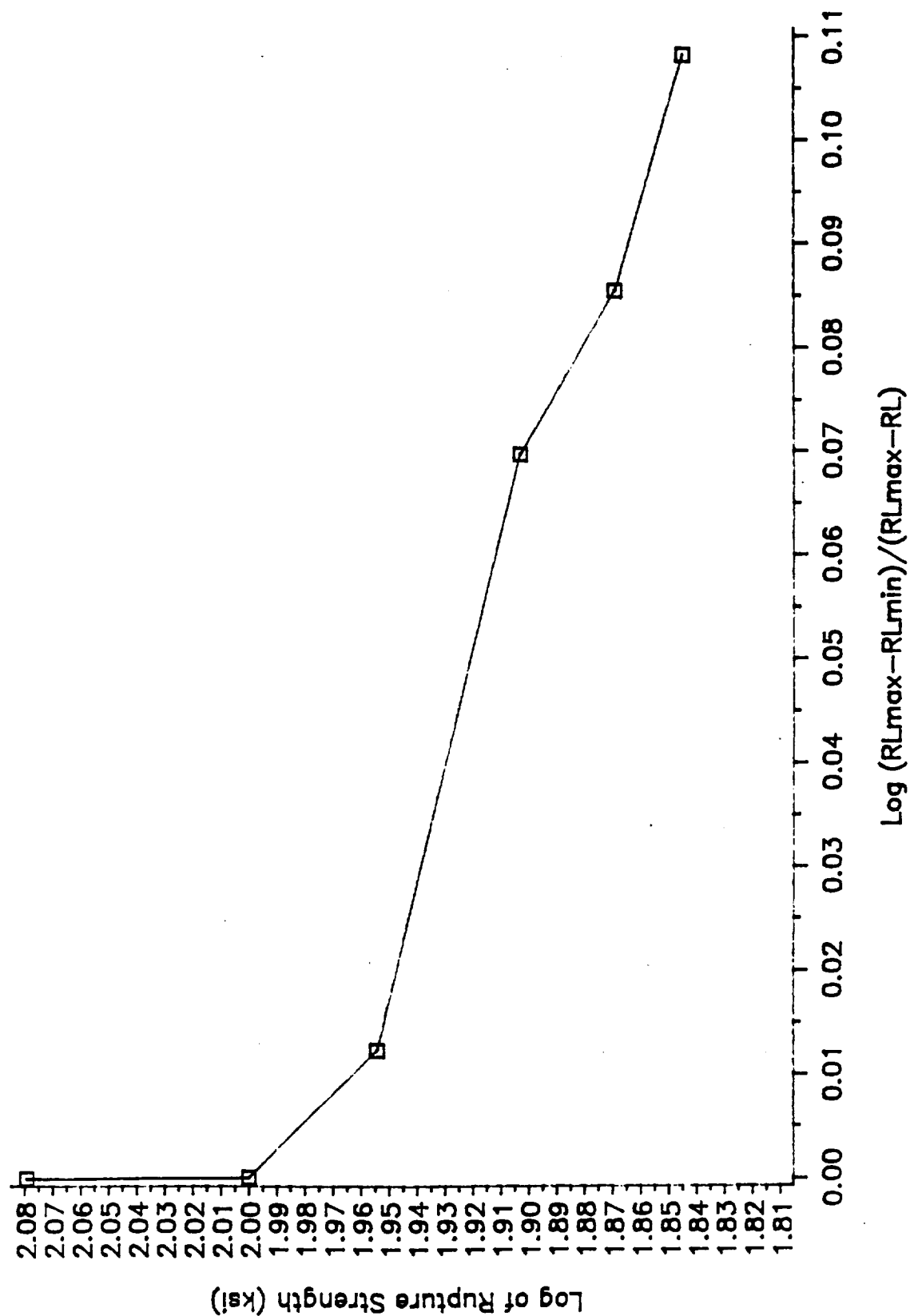
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



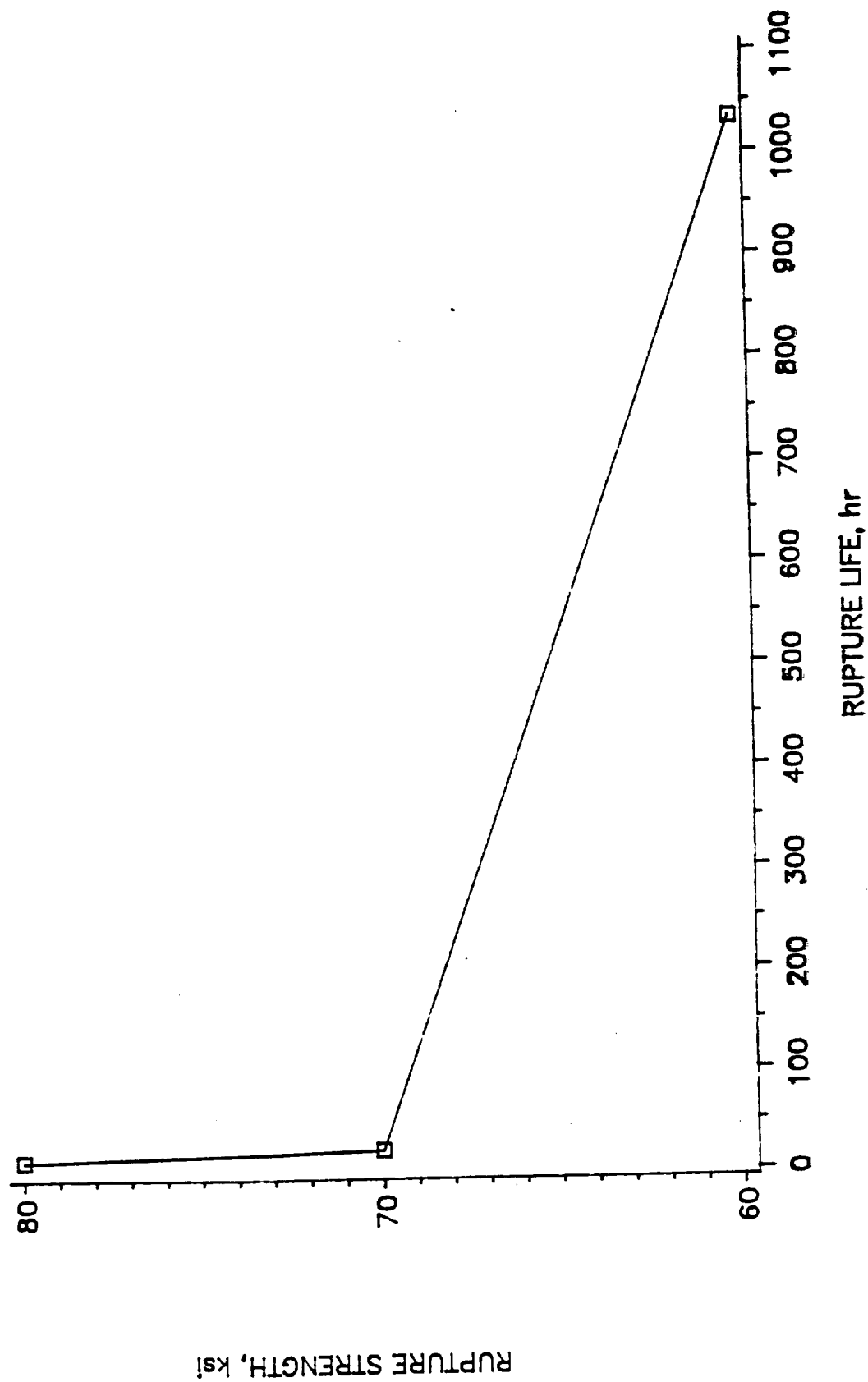
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



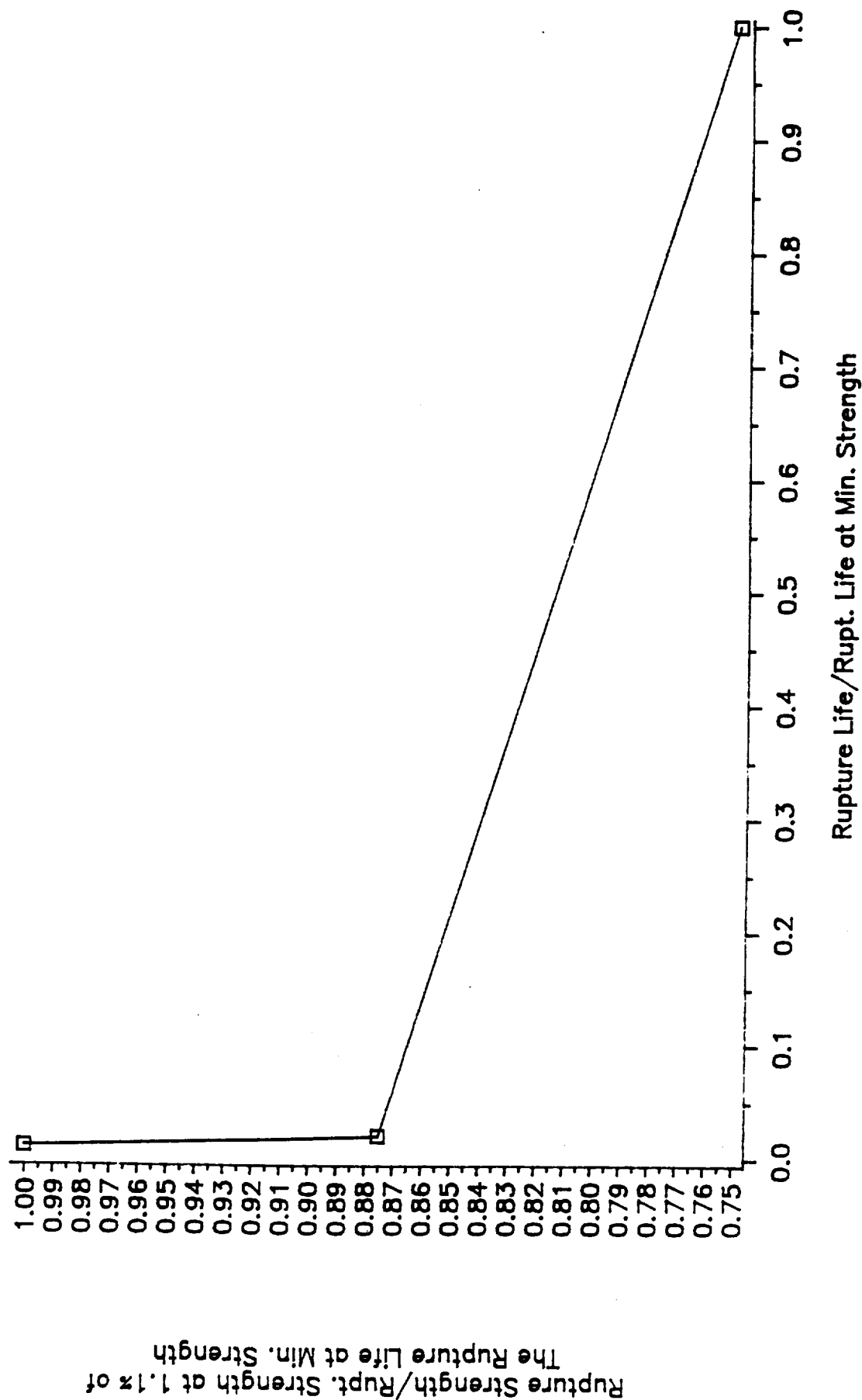
TEST TEMP. = 1200 F
NOTCHED Kt > 20
ANNLD AT 1750 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



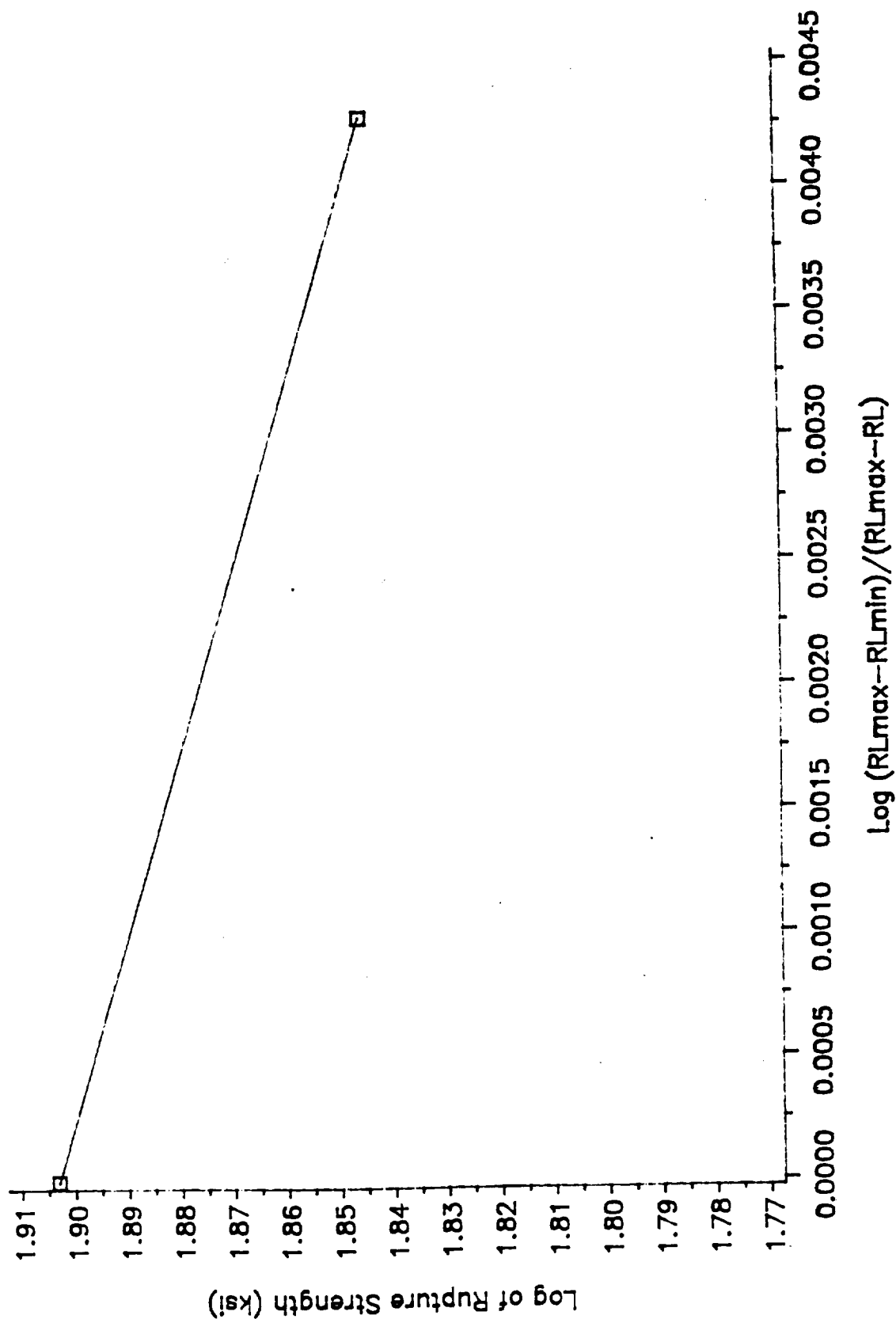
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



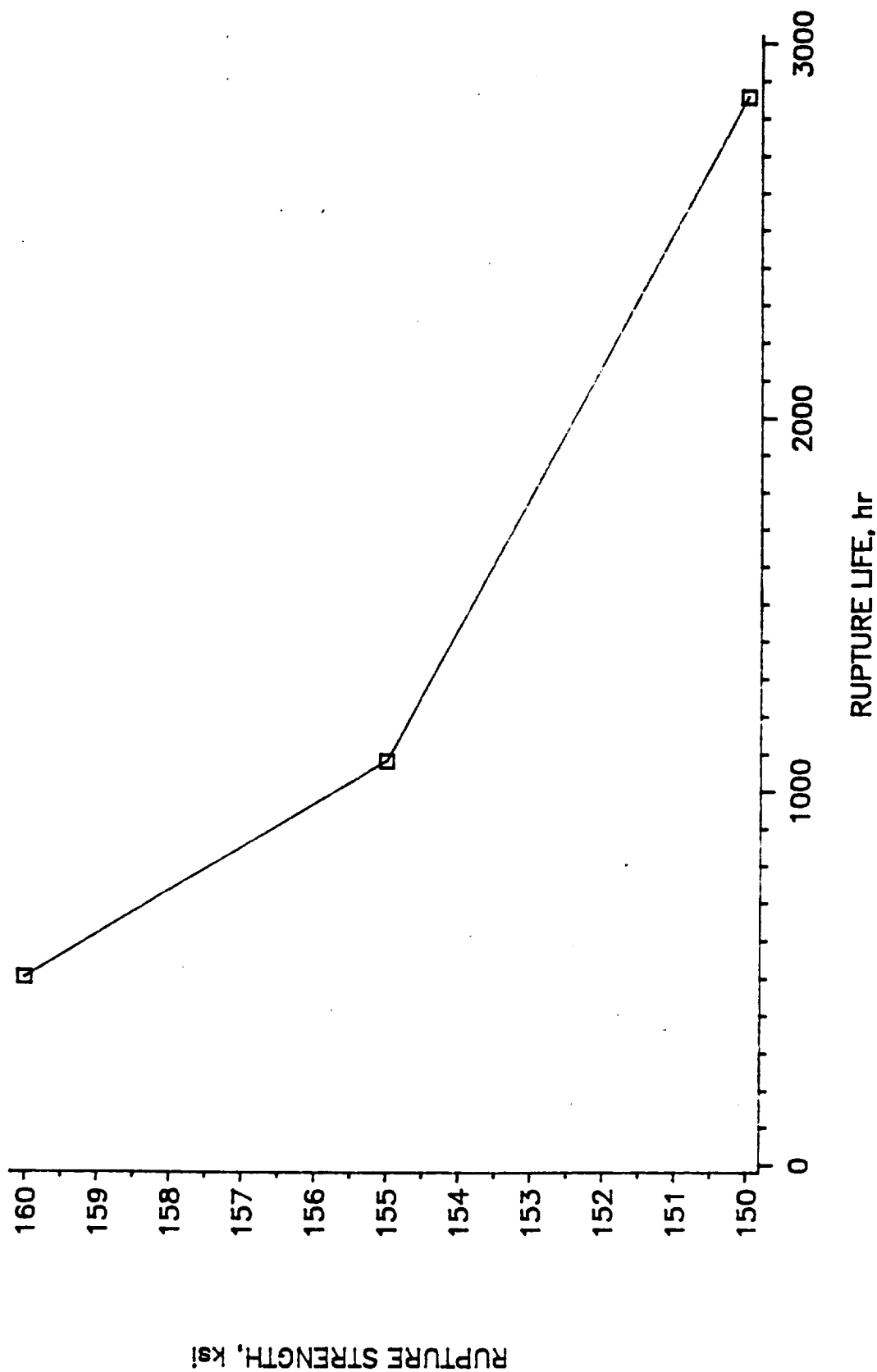
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



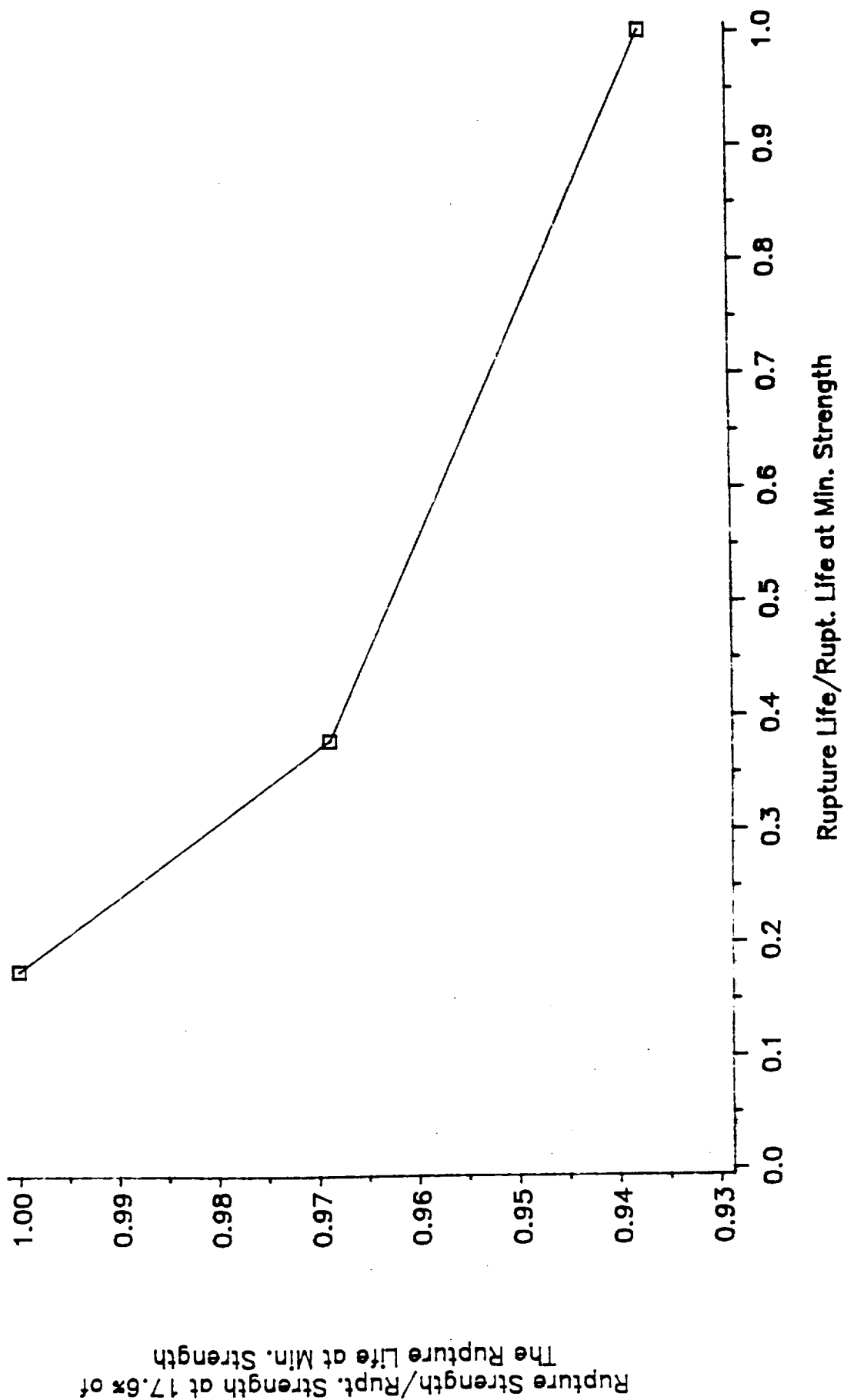
TEST TEMP. = 800 F
NOTCHED Kt > 20
ANNLD AT 1950 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



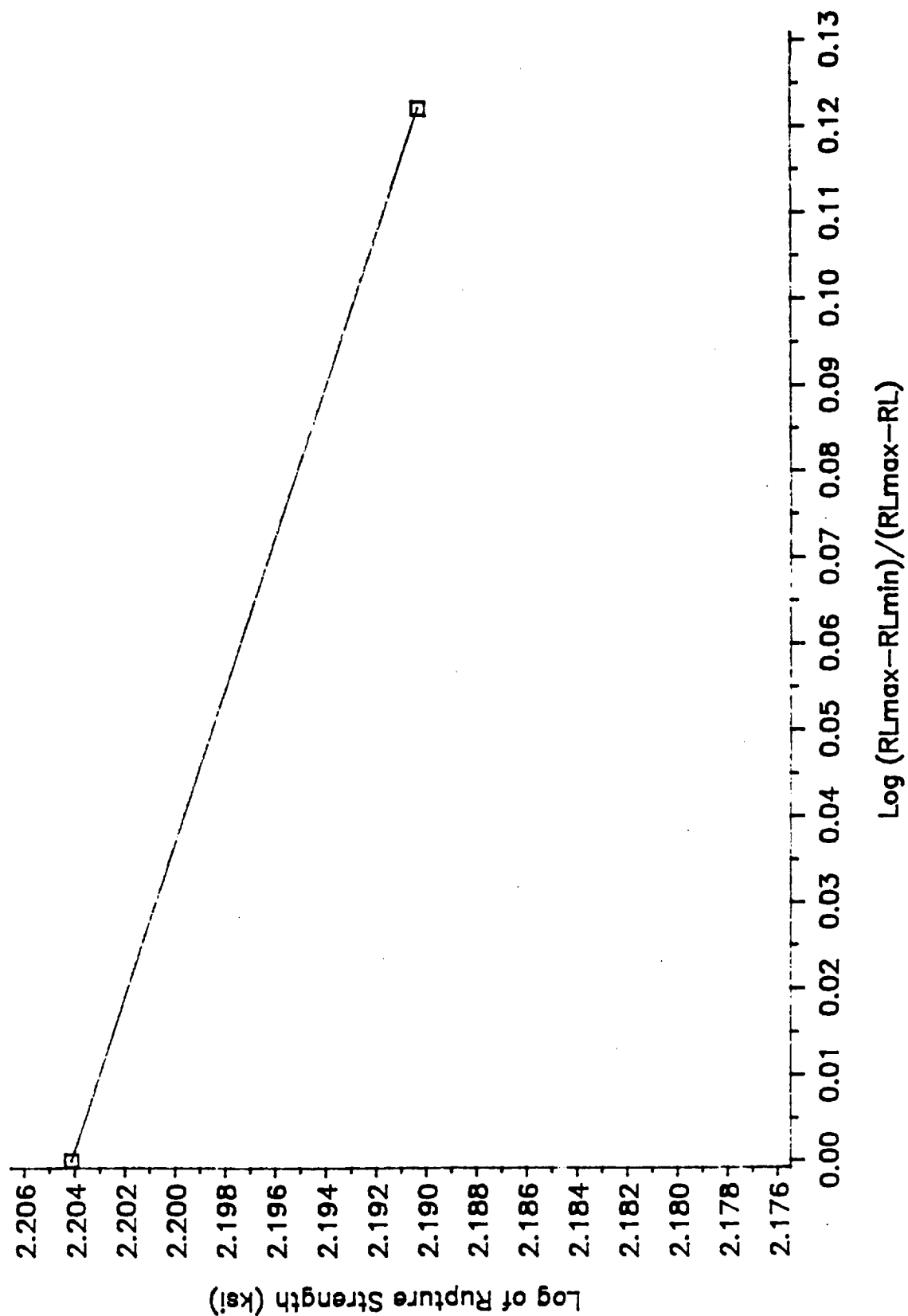
TEST TEMP. = 800 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



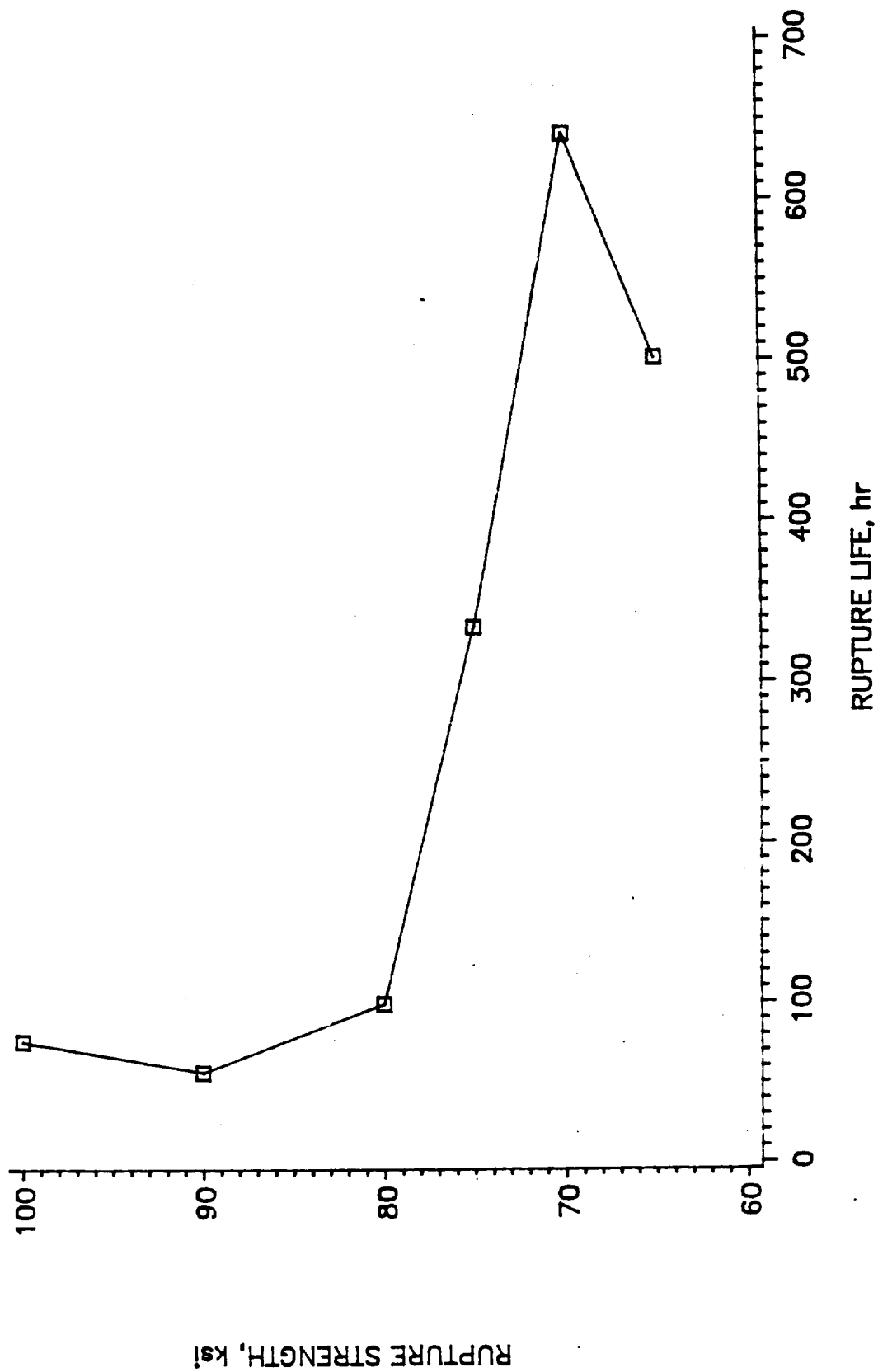
TEST TEMP. = 800 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



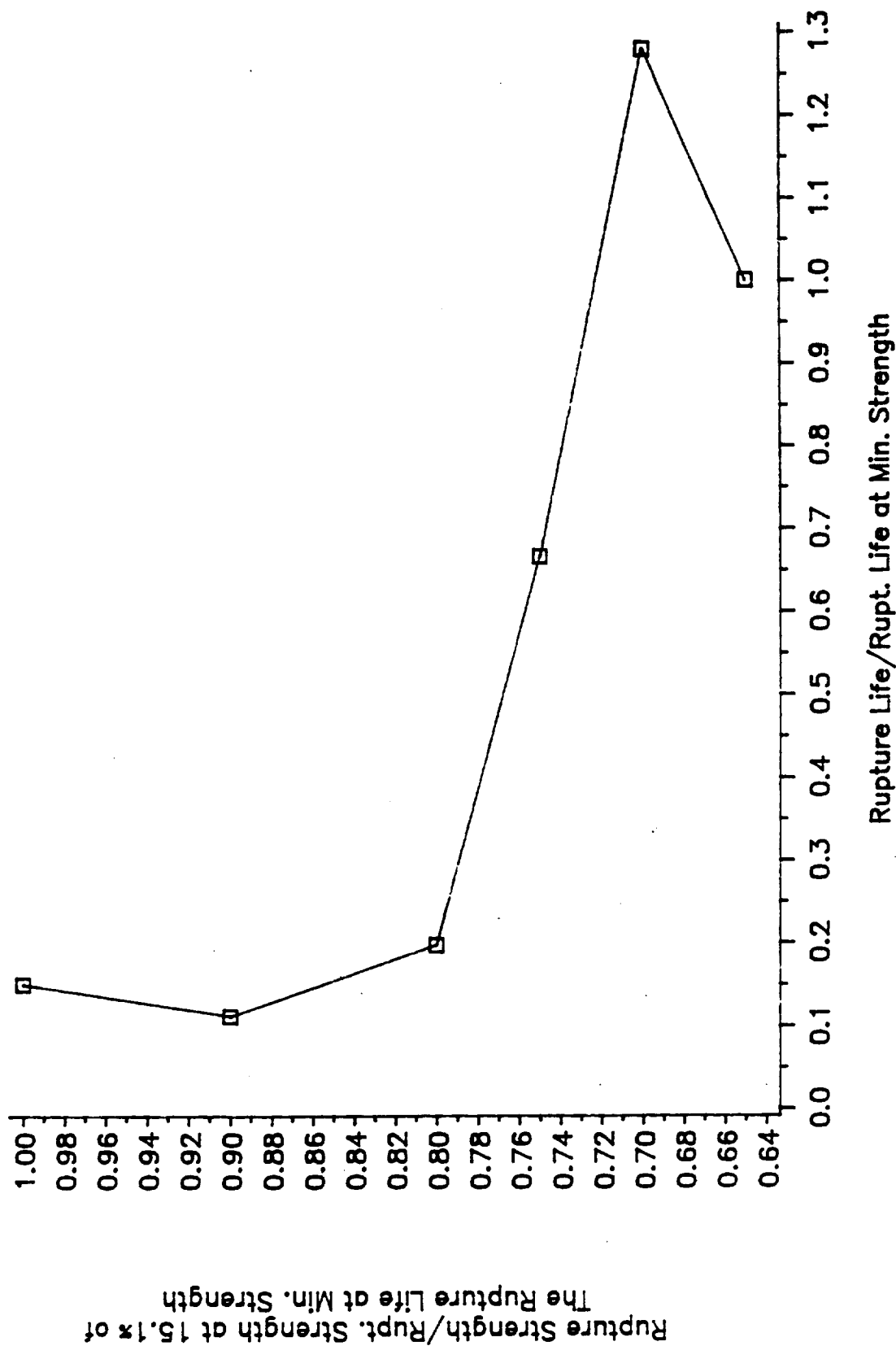
TEST TEMP. = 1000 F
NOTCHED Kt > 20
ANNLD AT 1950 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



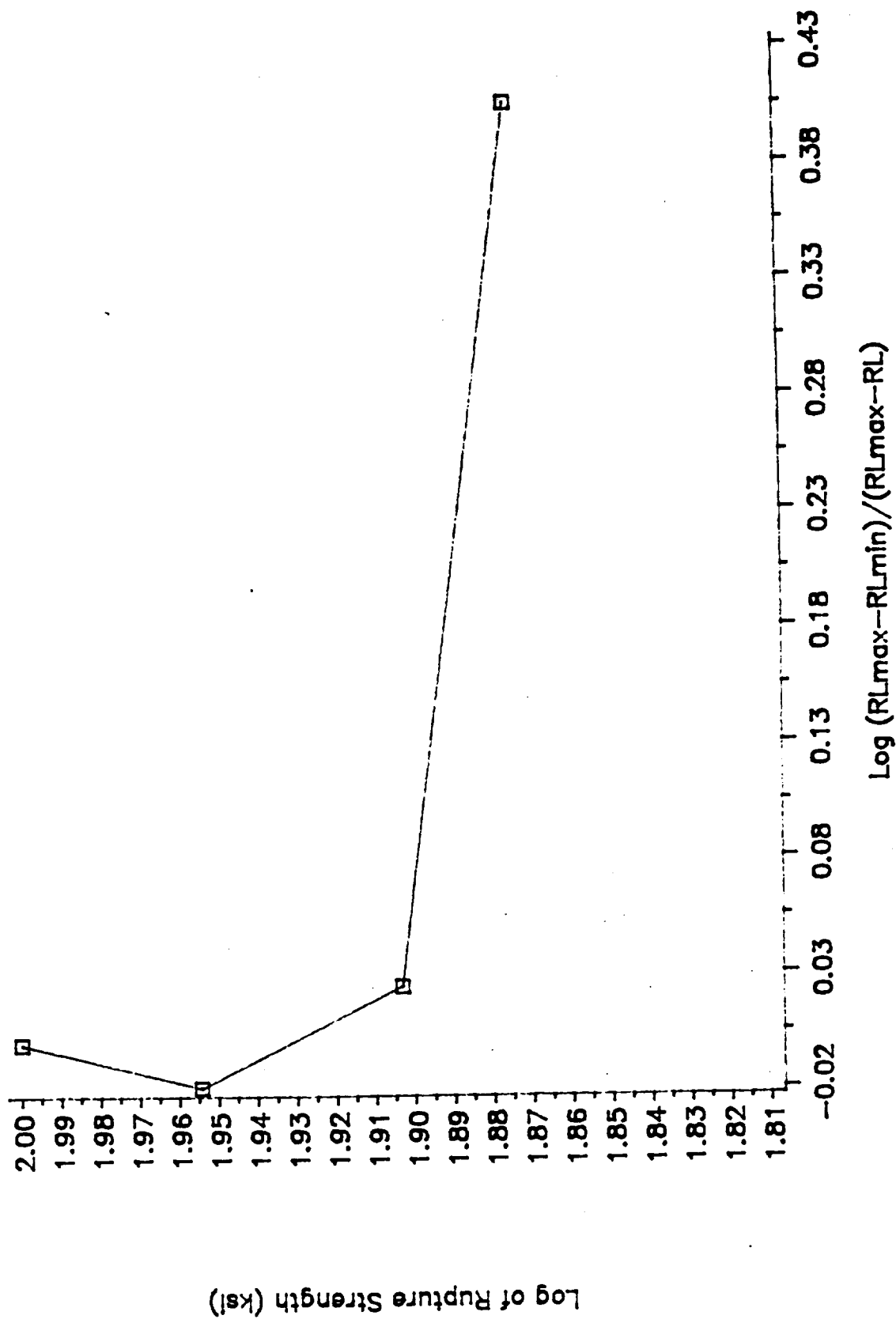
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



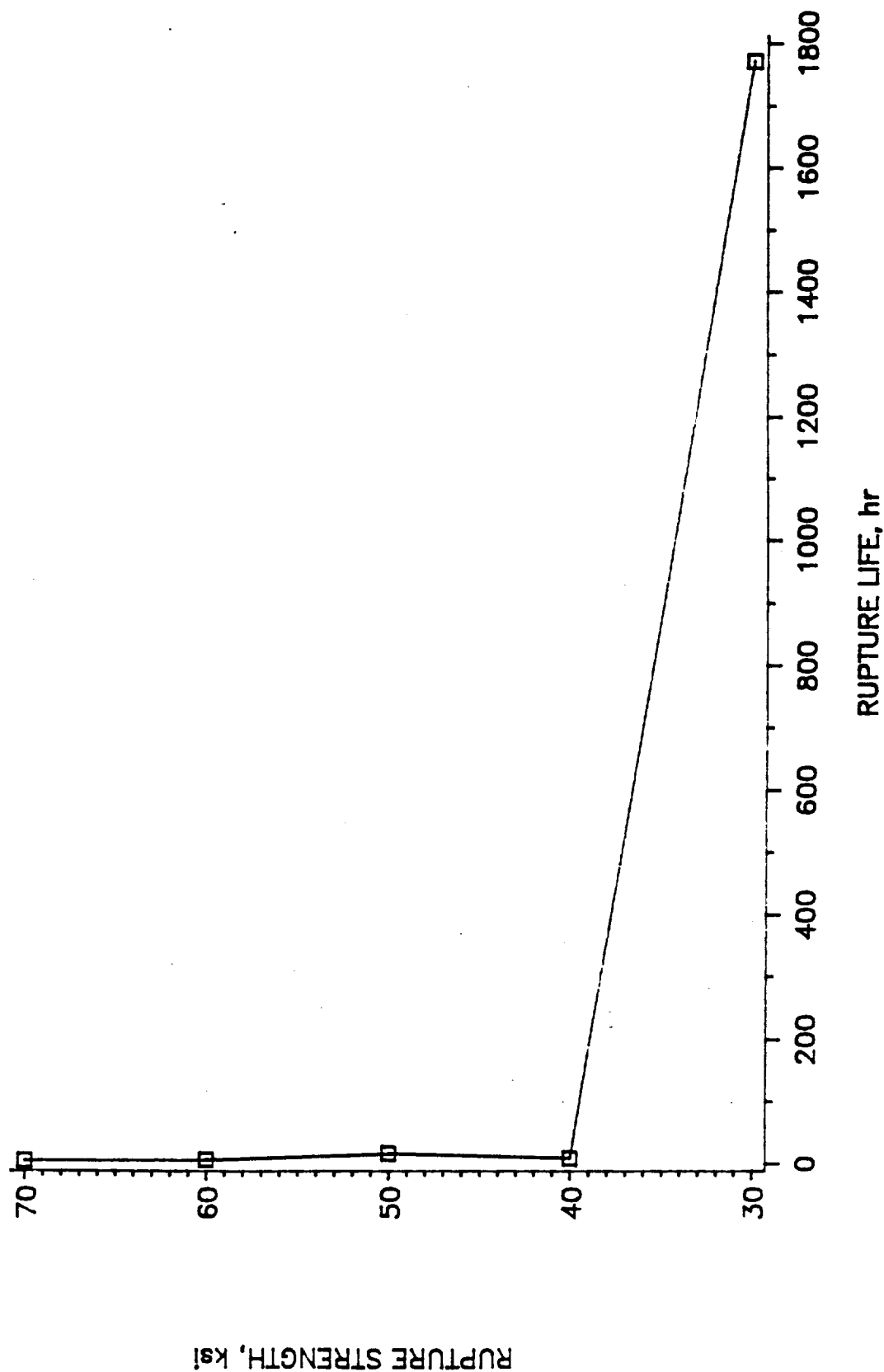
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



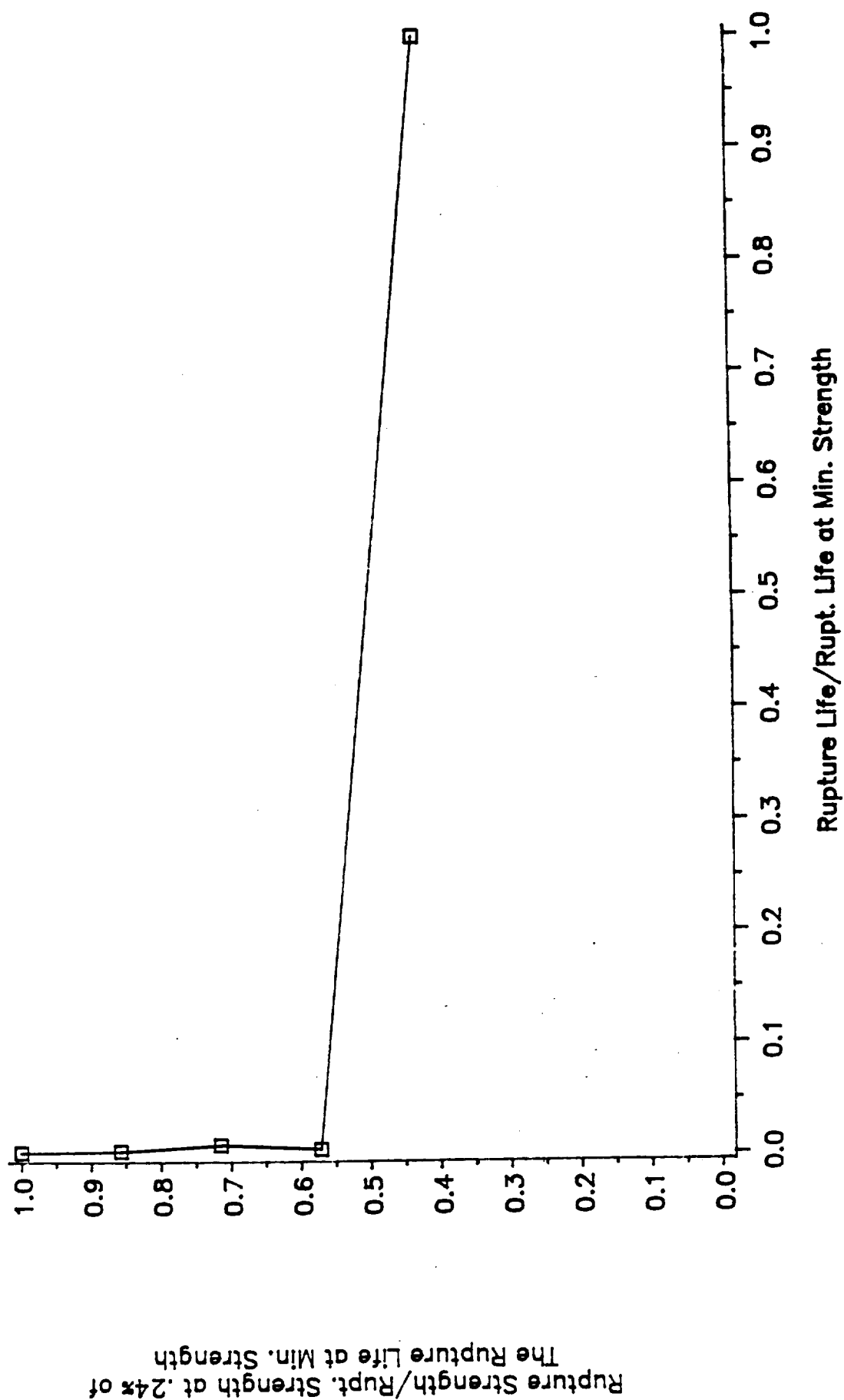
TEST TEMP. = 1200 F
NOTCHED Kt > 20
ANNLD AT 1950 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



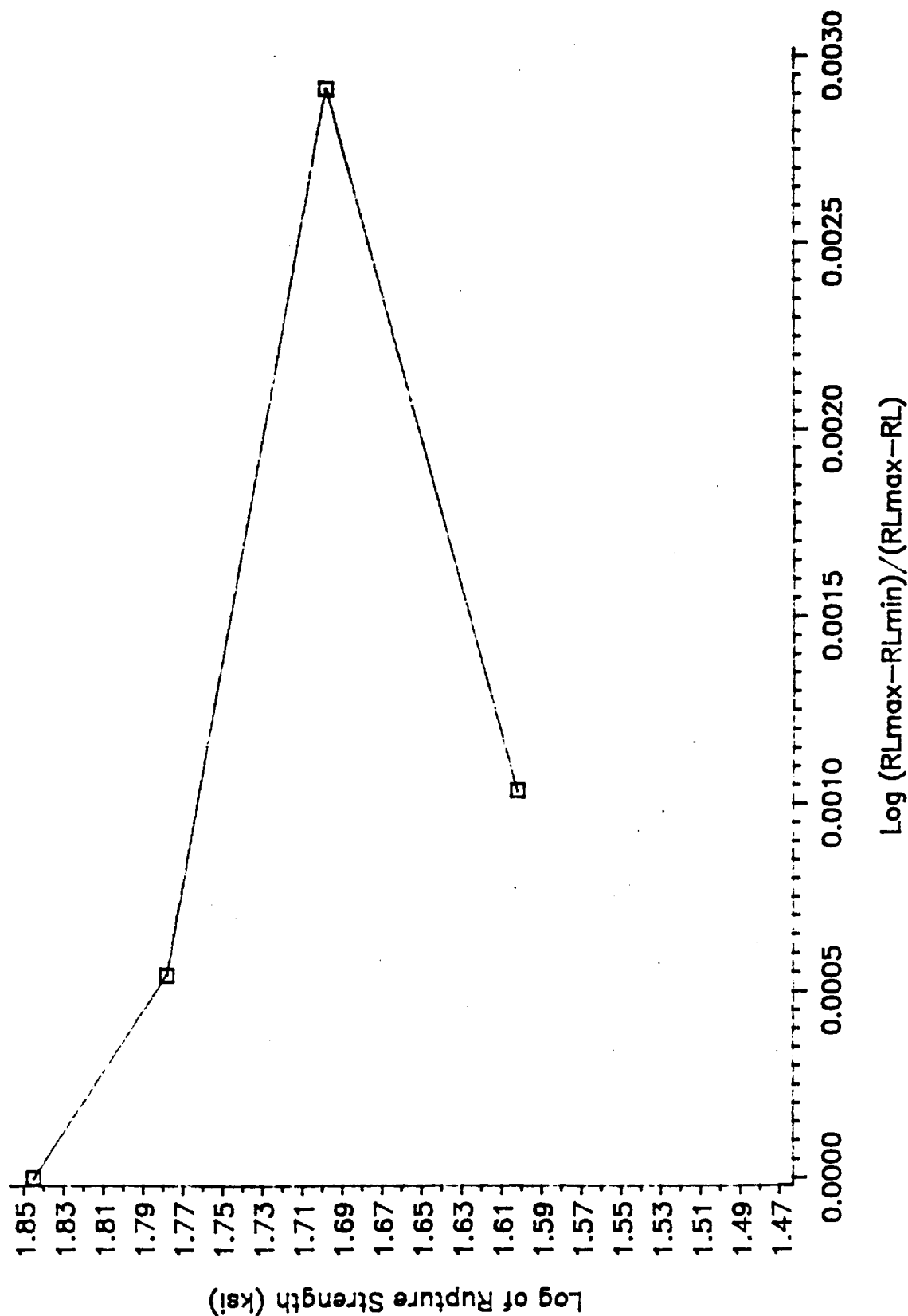
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



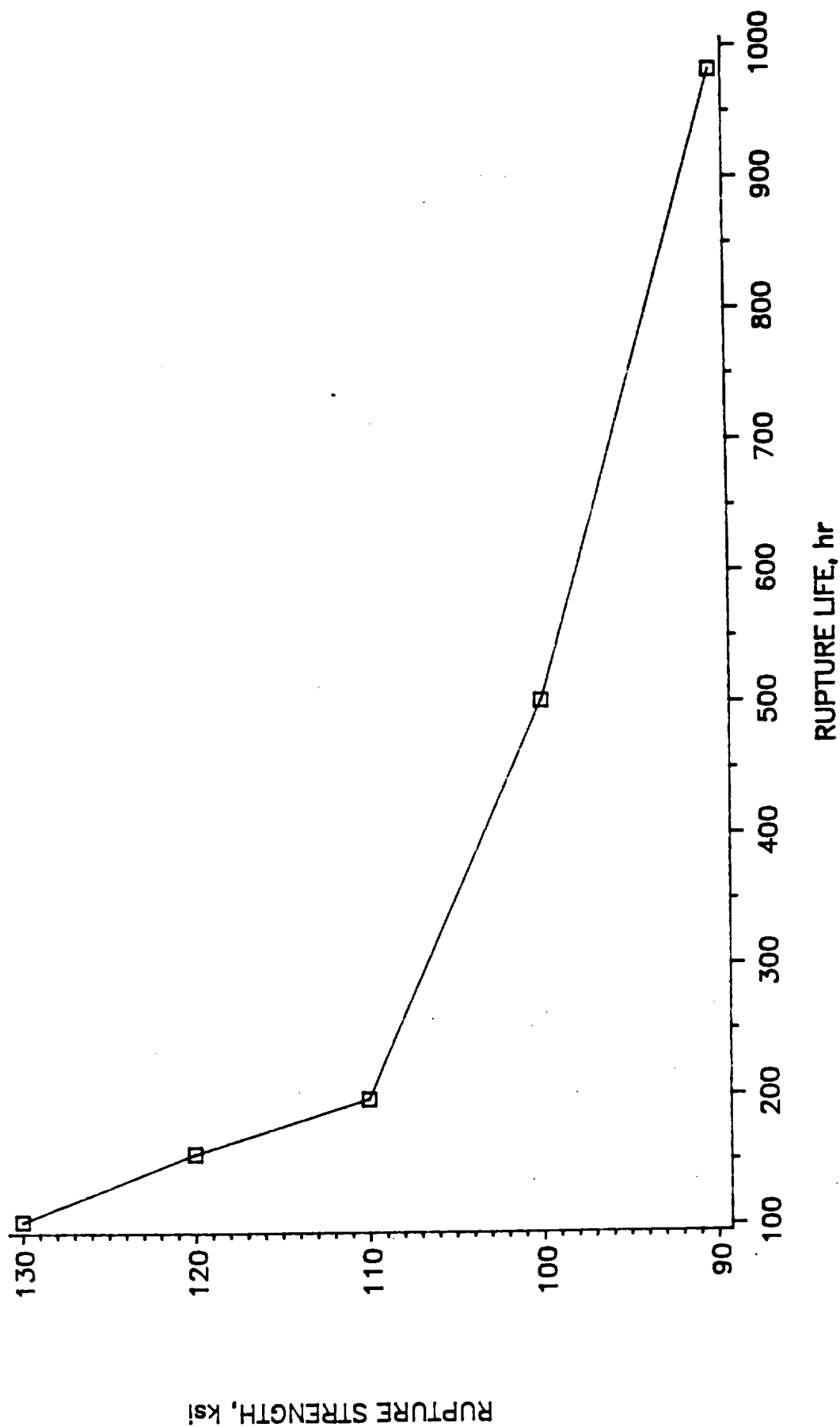
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



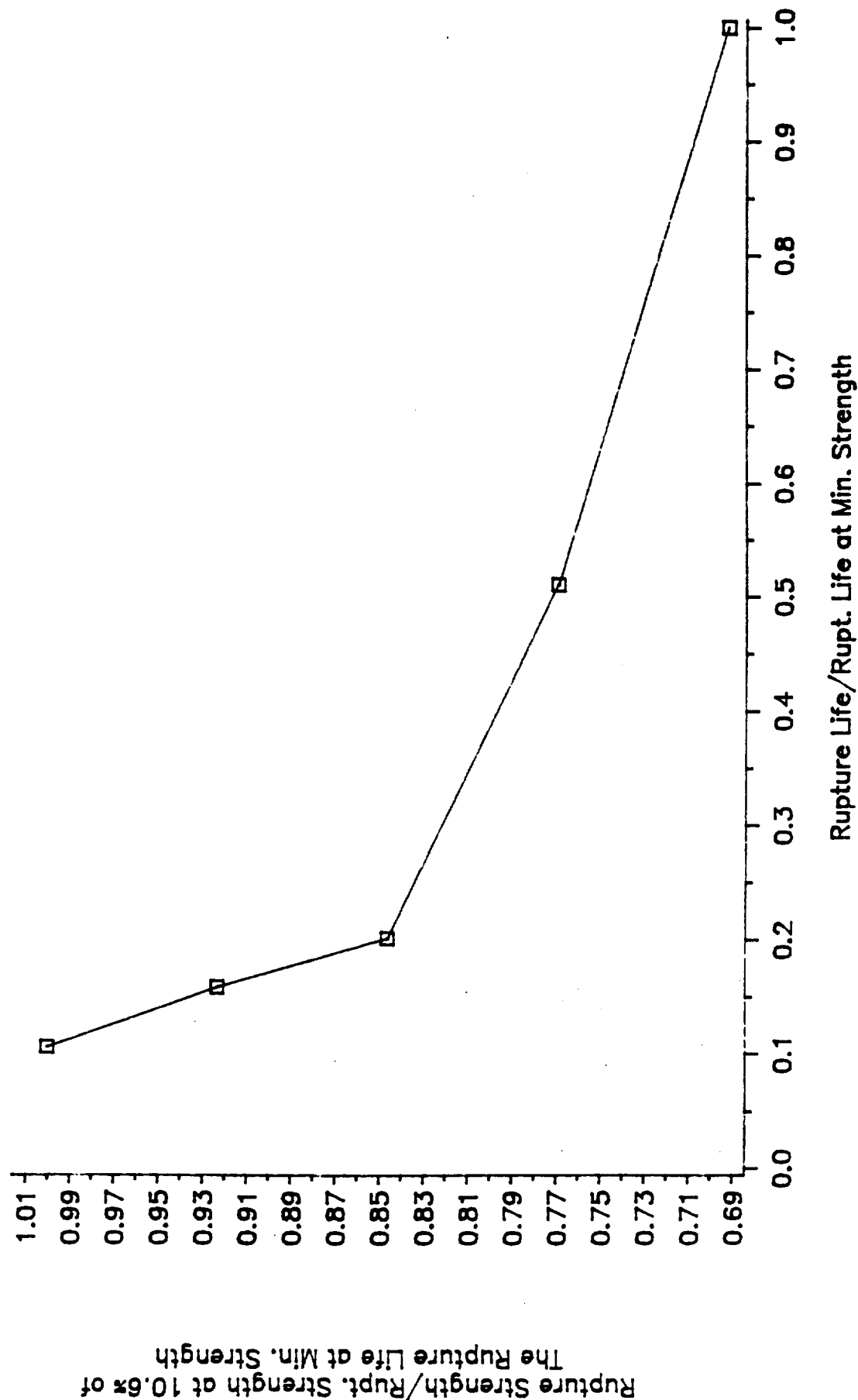
TEST TEMP. = 1000 F
NOTCHED $K_t=6.0$
ANNELED AT 1950 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



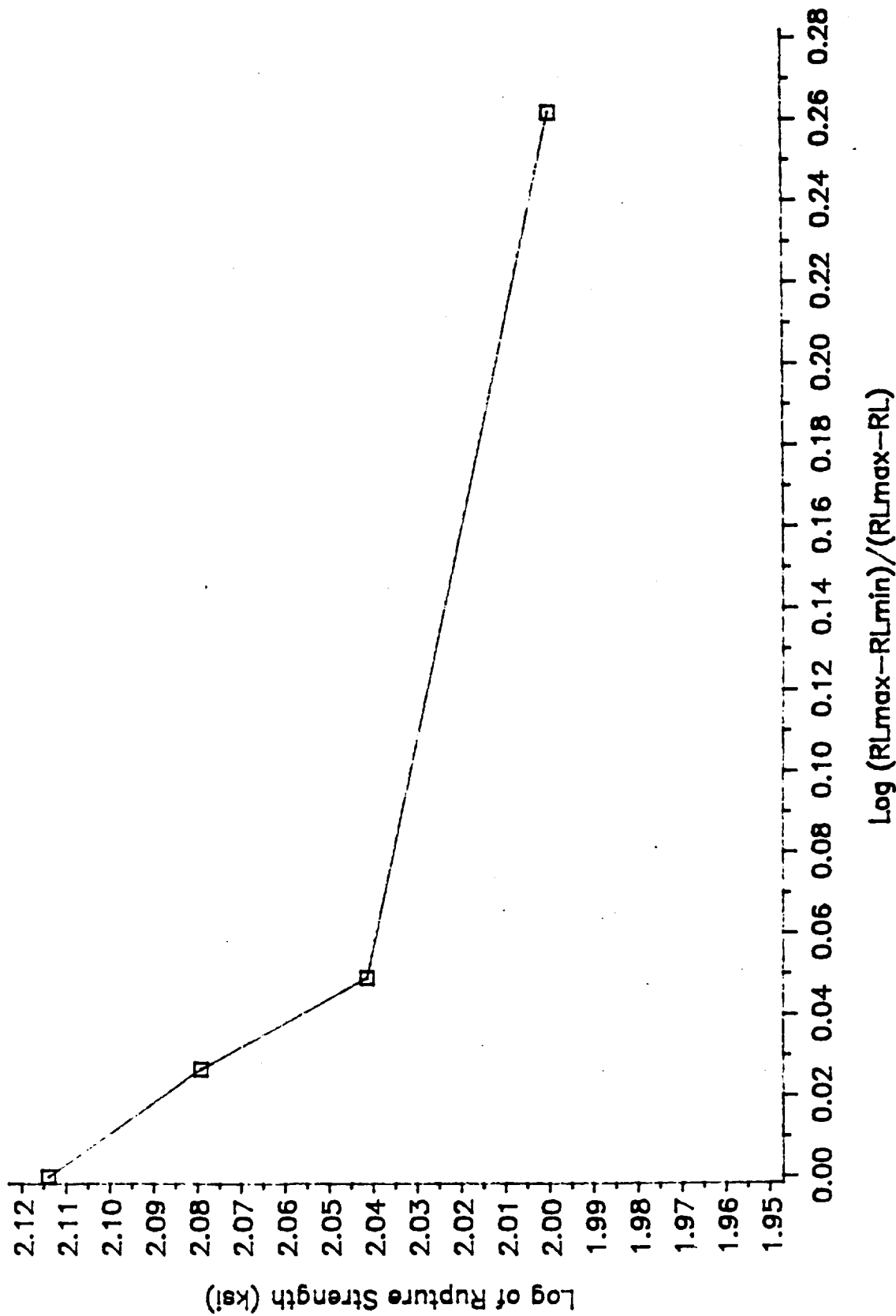
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



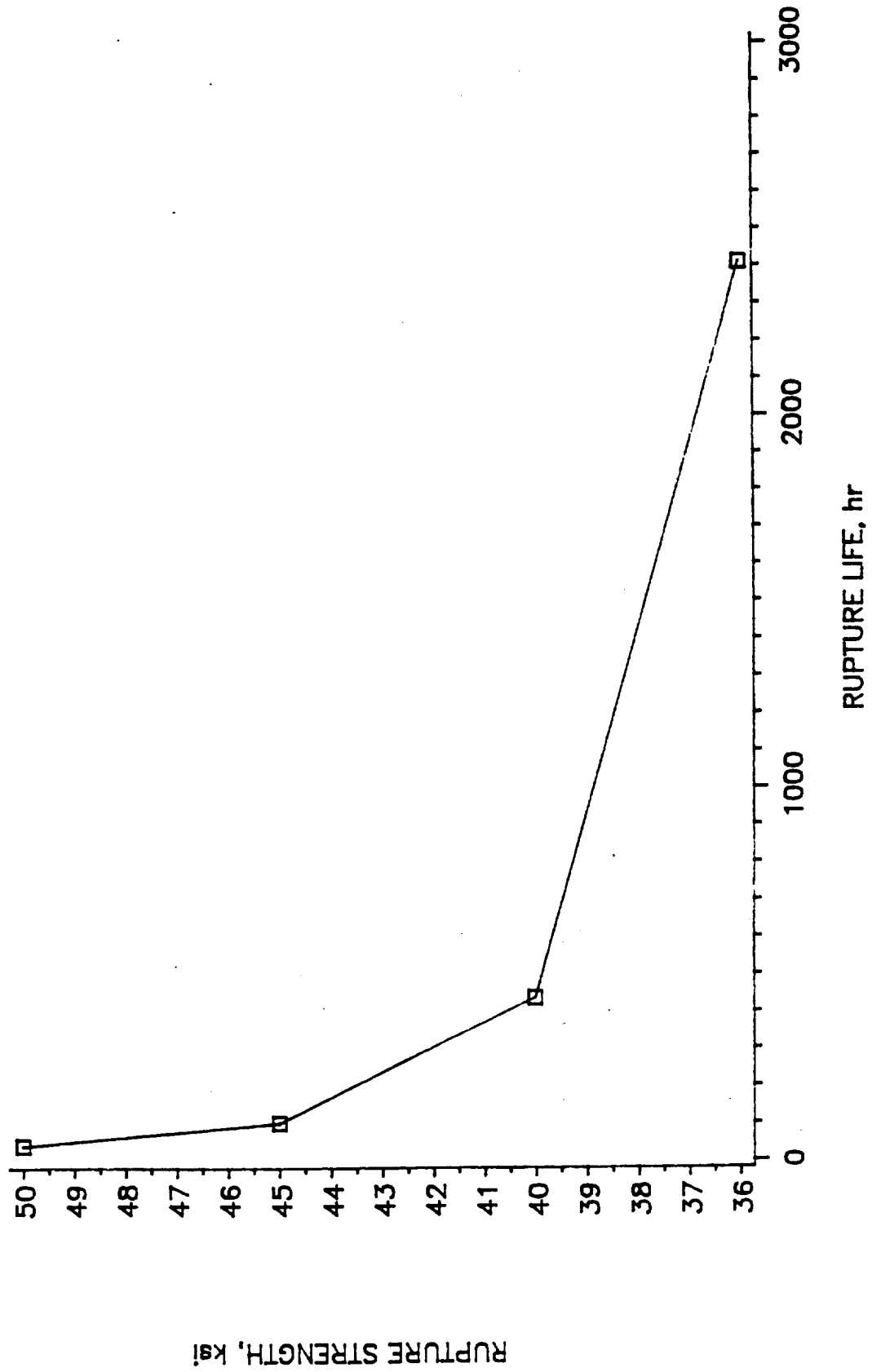
TEST TEMP. = 1000 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



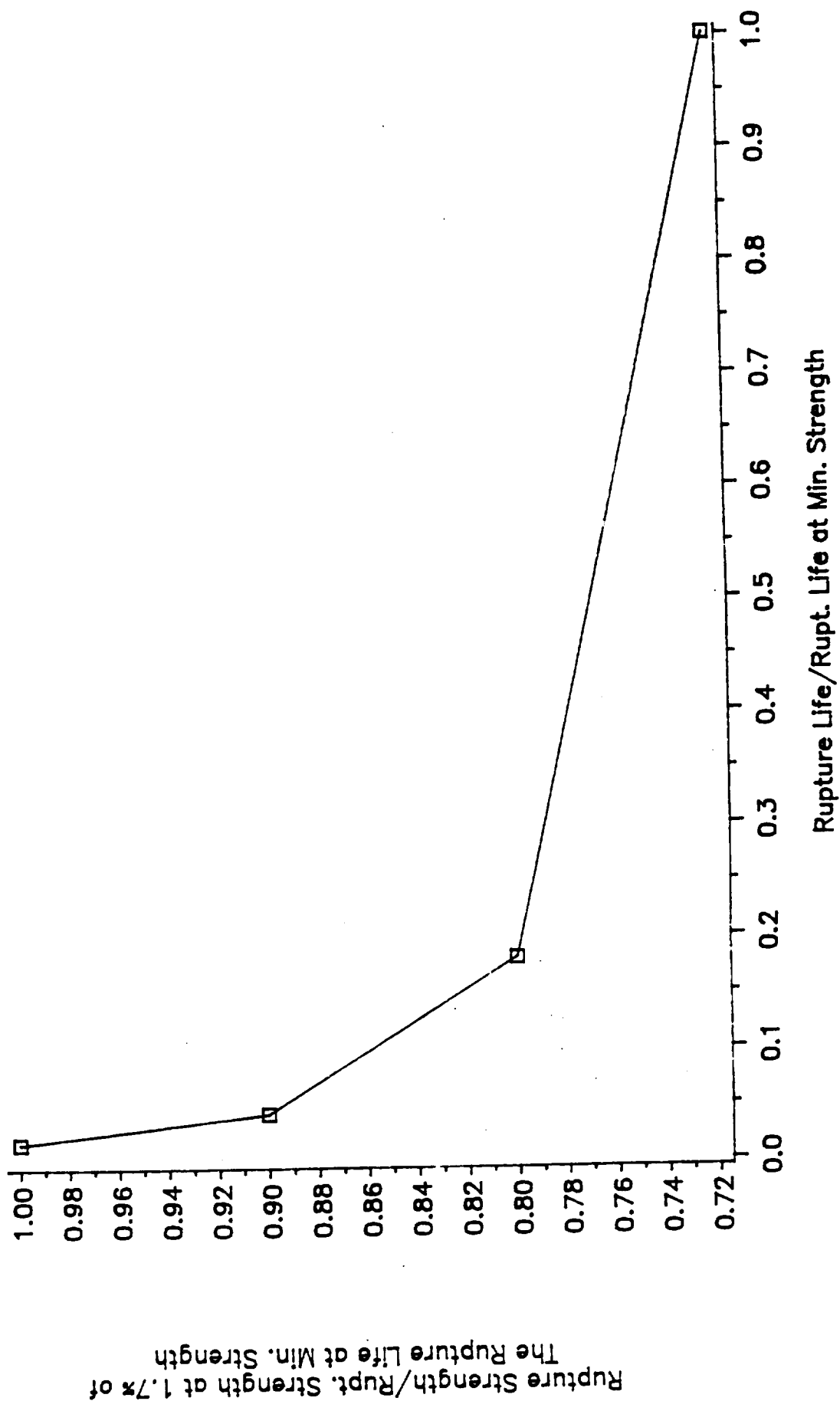
TEST TEMP. = 1200 F
NOTCHED $K_t=6.0$
ANNLD AT 1950 F & AGED

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



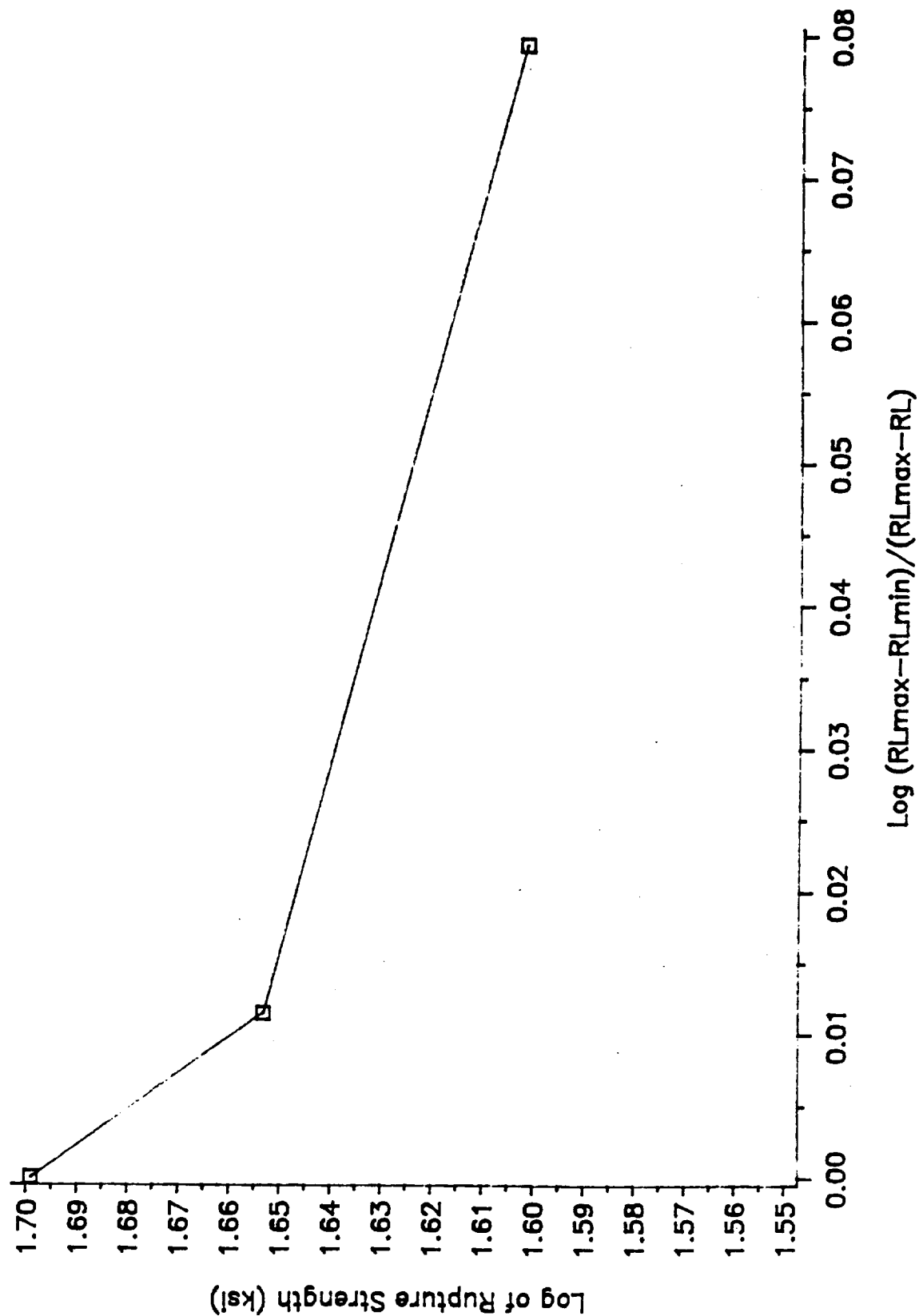
TEST TEMP. = 1200 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



TEST TEMP. = 1200 F

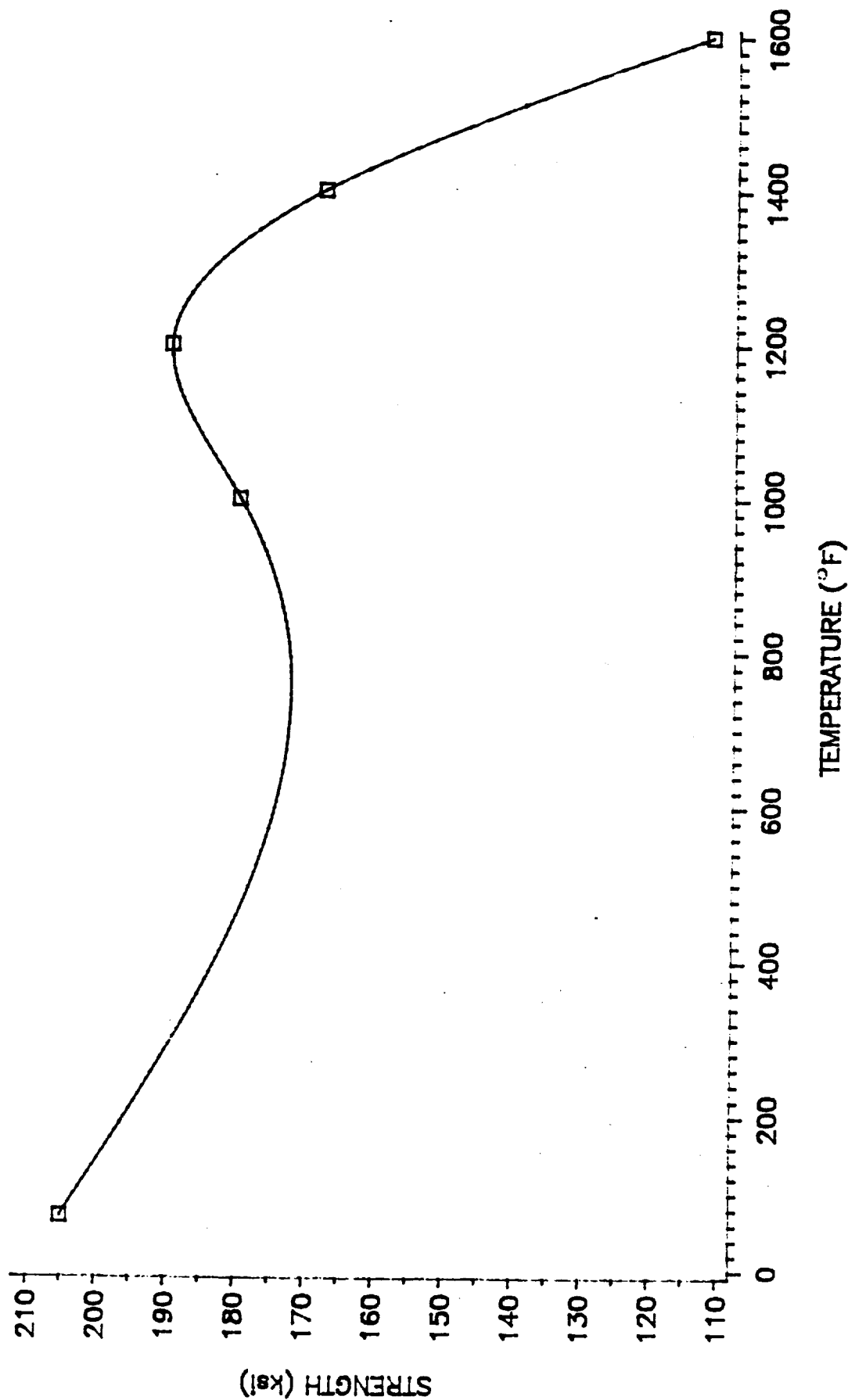
EFFECT OF TIME ON RUPTURE STRENGTH FOR INCONEL 718



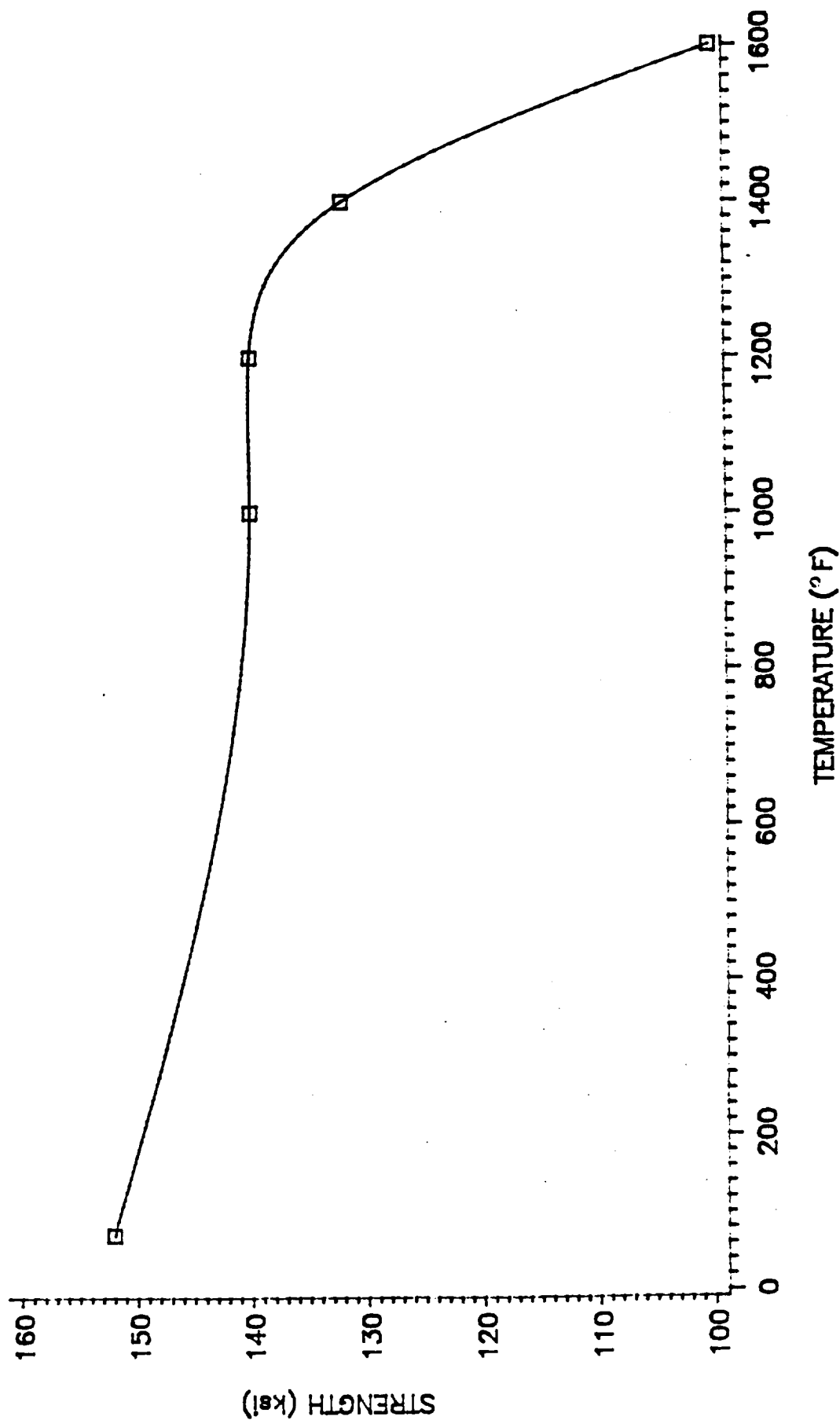
13.3 Tensile and Fatigue Data Plots of Nickel-Base Superalloys

Heat-Treated Bar
Wrought Alloy

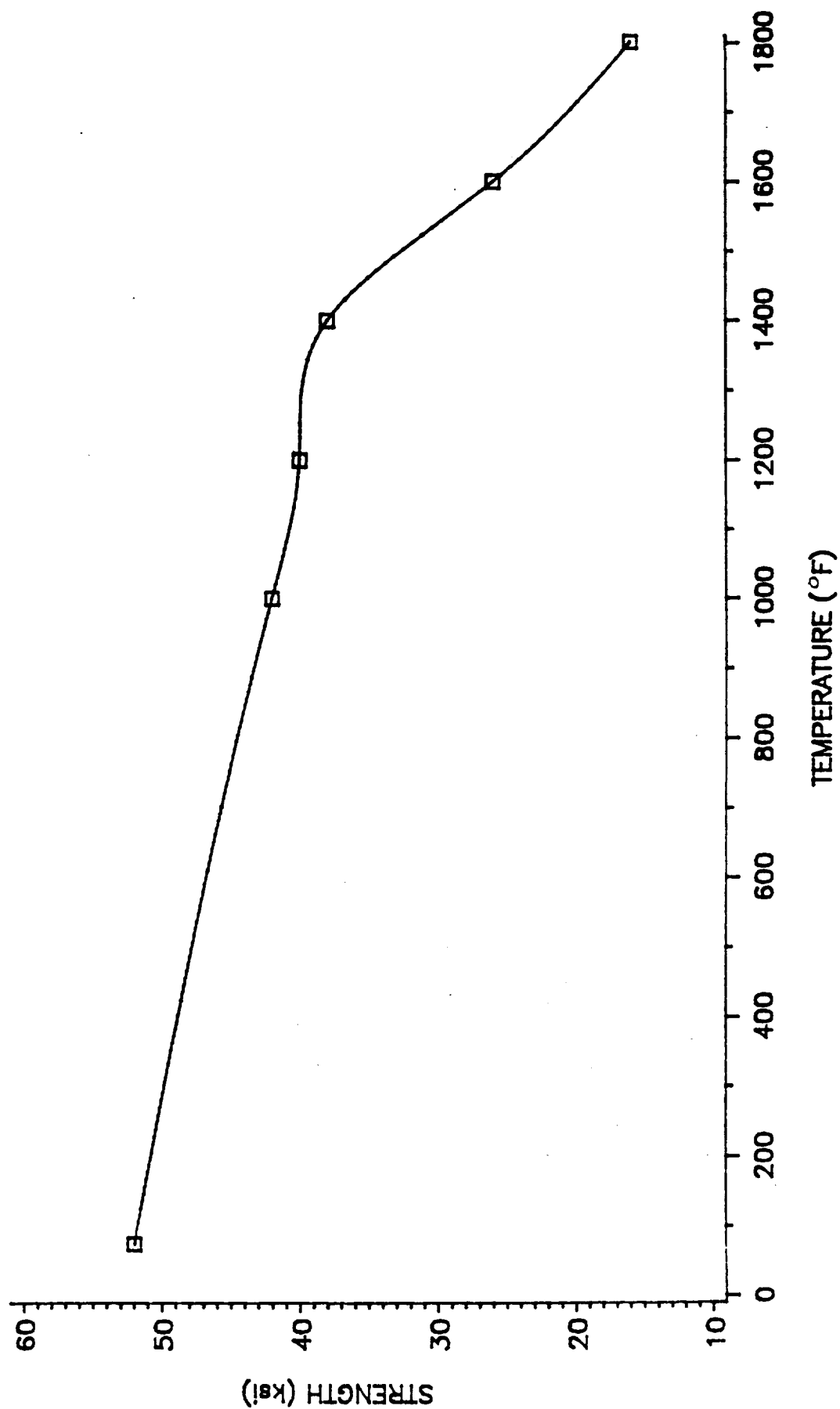
EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR ASTROLOY



EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR ASTROLOY

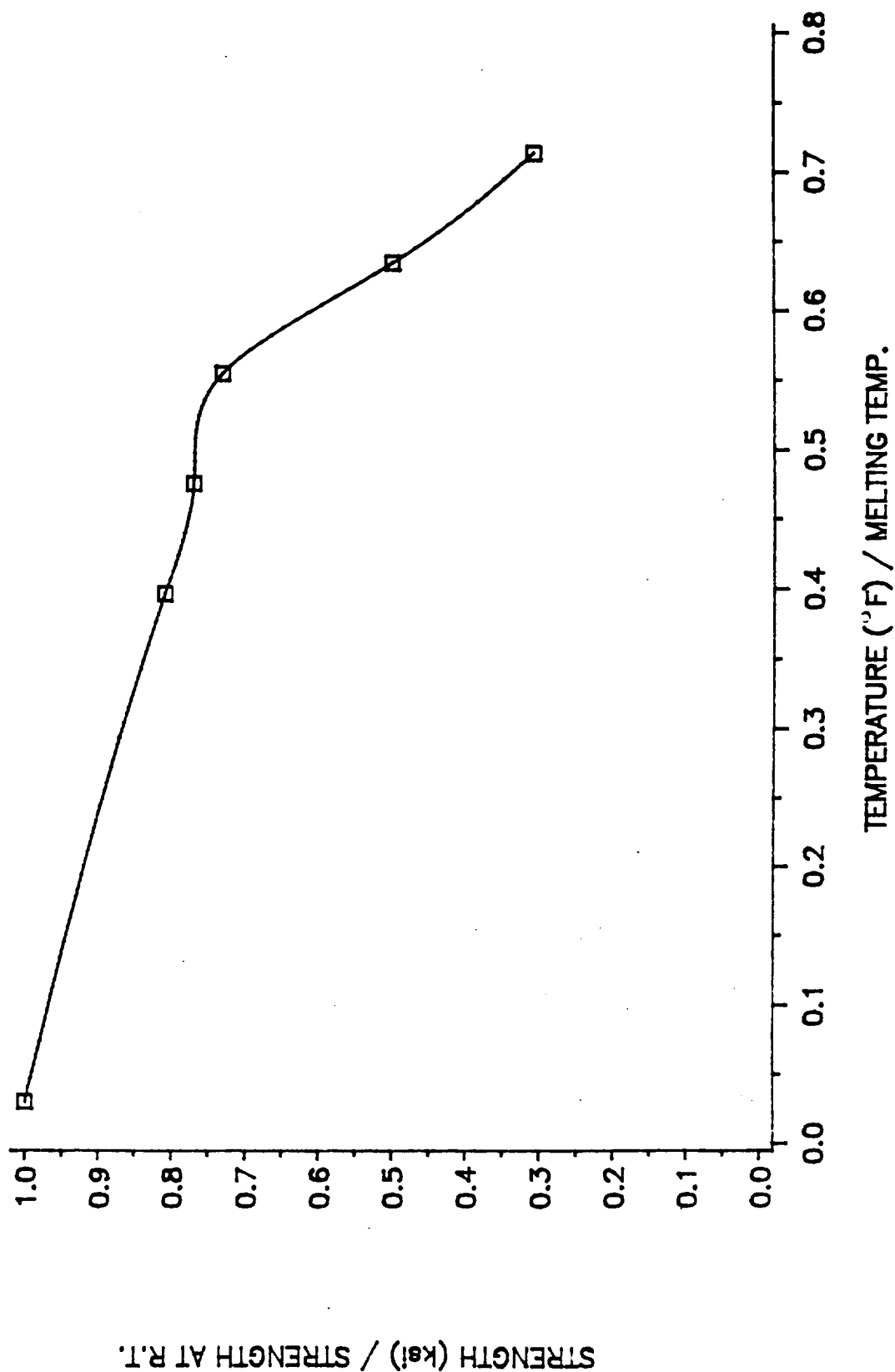


EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR HASTELLOY X



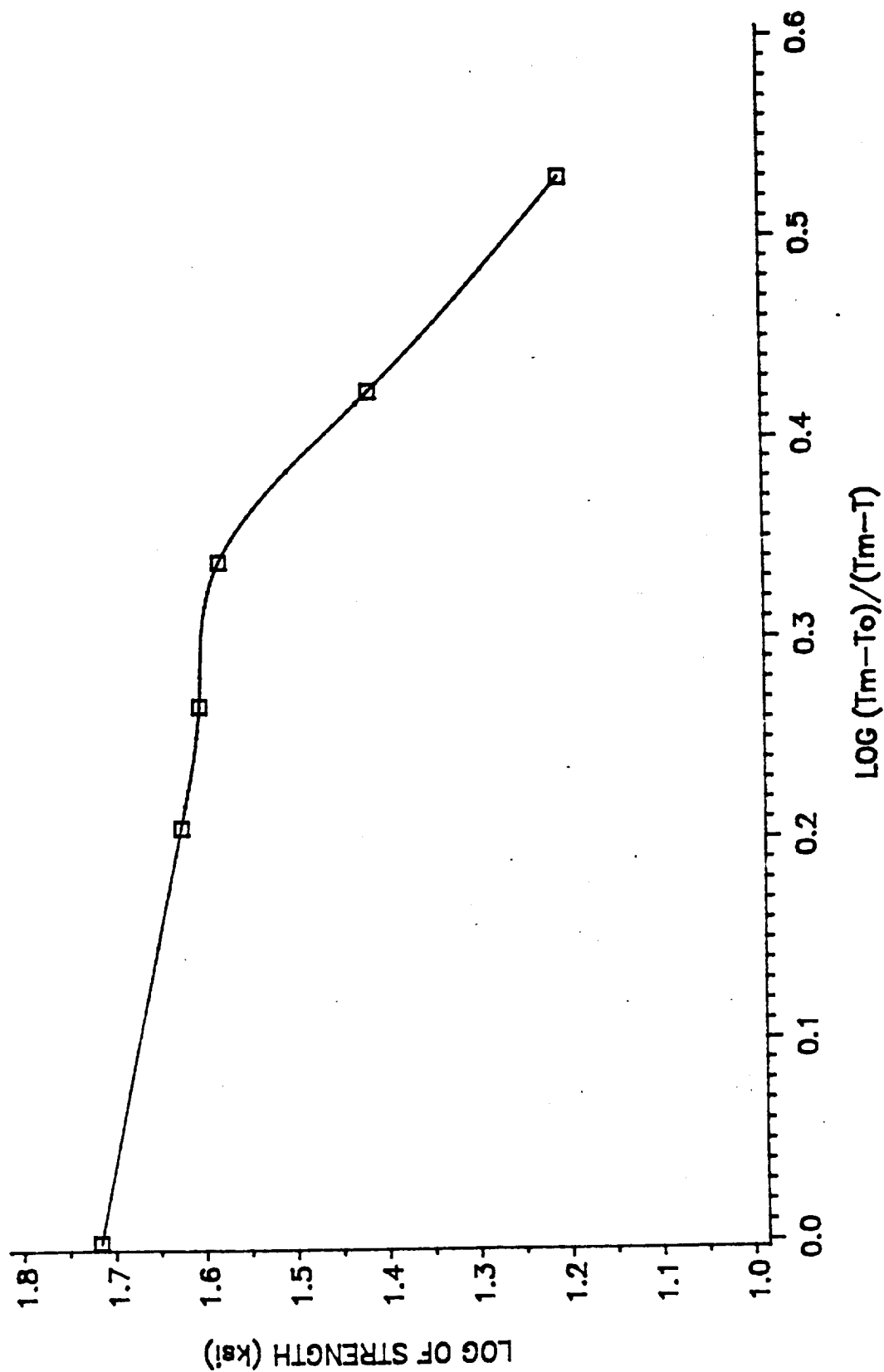
R.T.=75 F, T_m=2523 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR HASTELLOY X



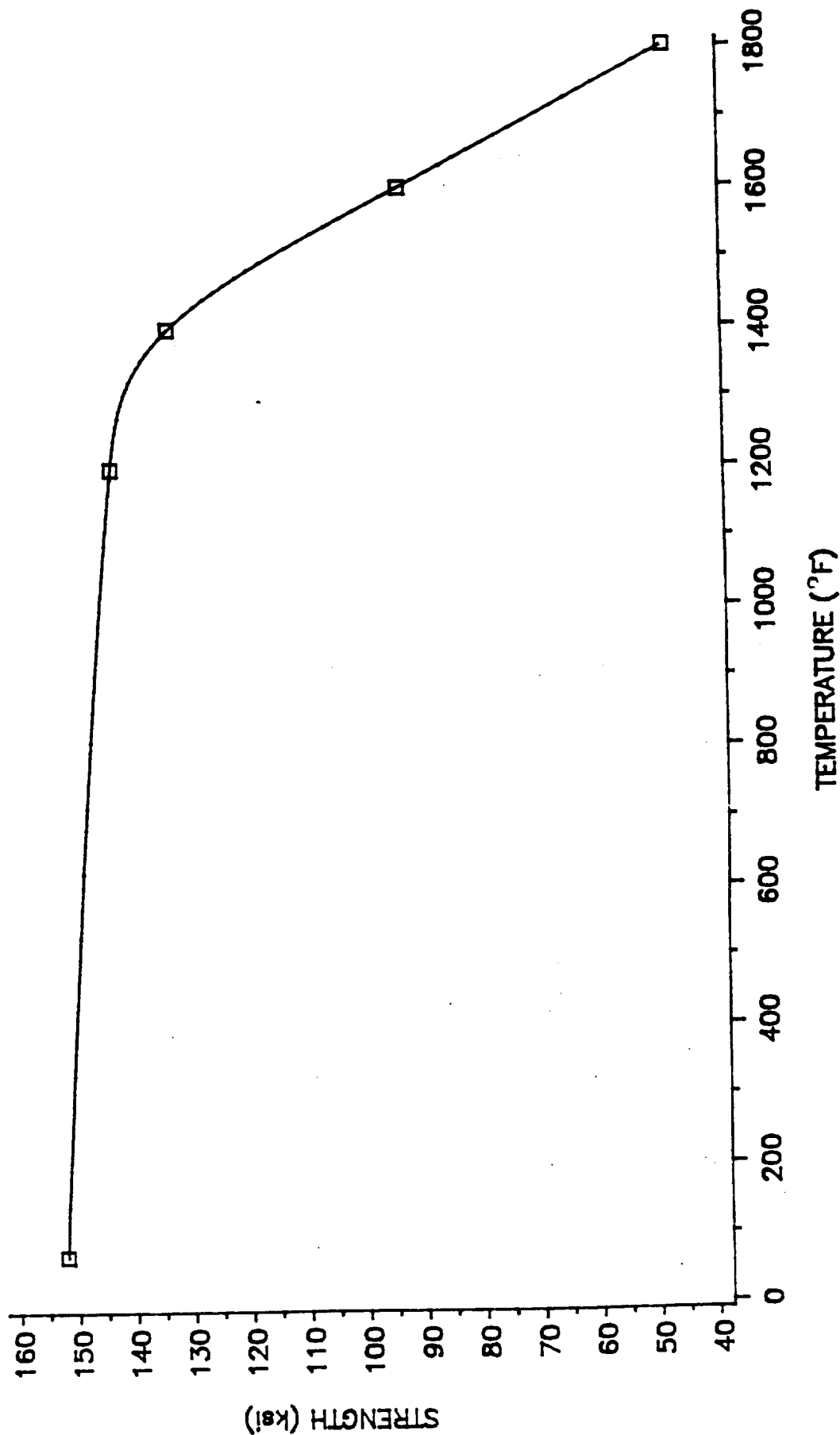
$T_0=75$ F, $T_m=2523$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR HASTELLOY X

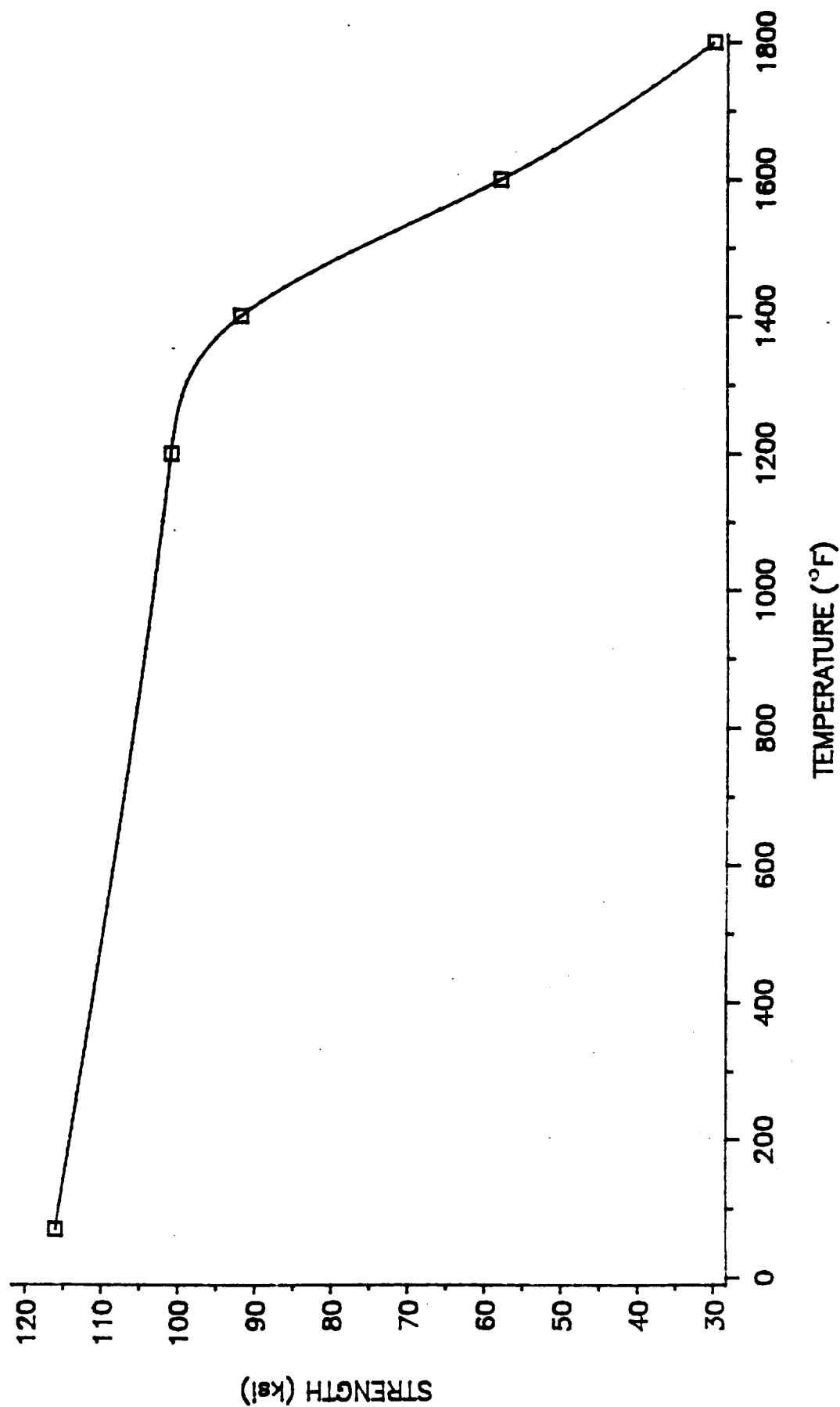


2120 F / 4/RAC+1830 F / 8/RAC+
1830 F / 24/AC+1290 F / 16/AC

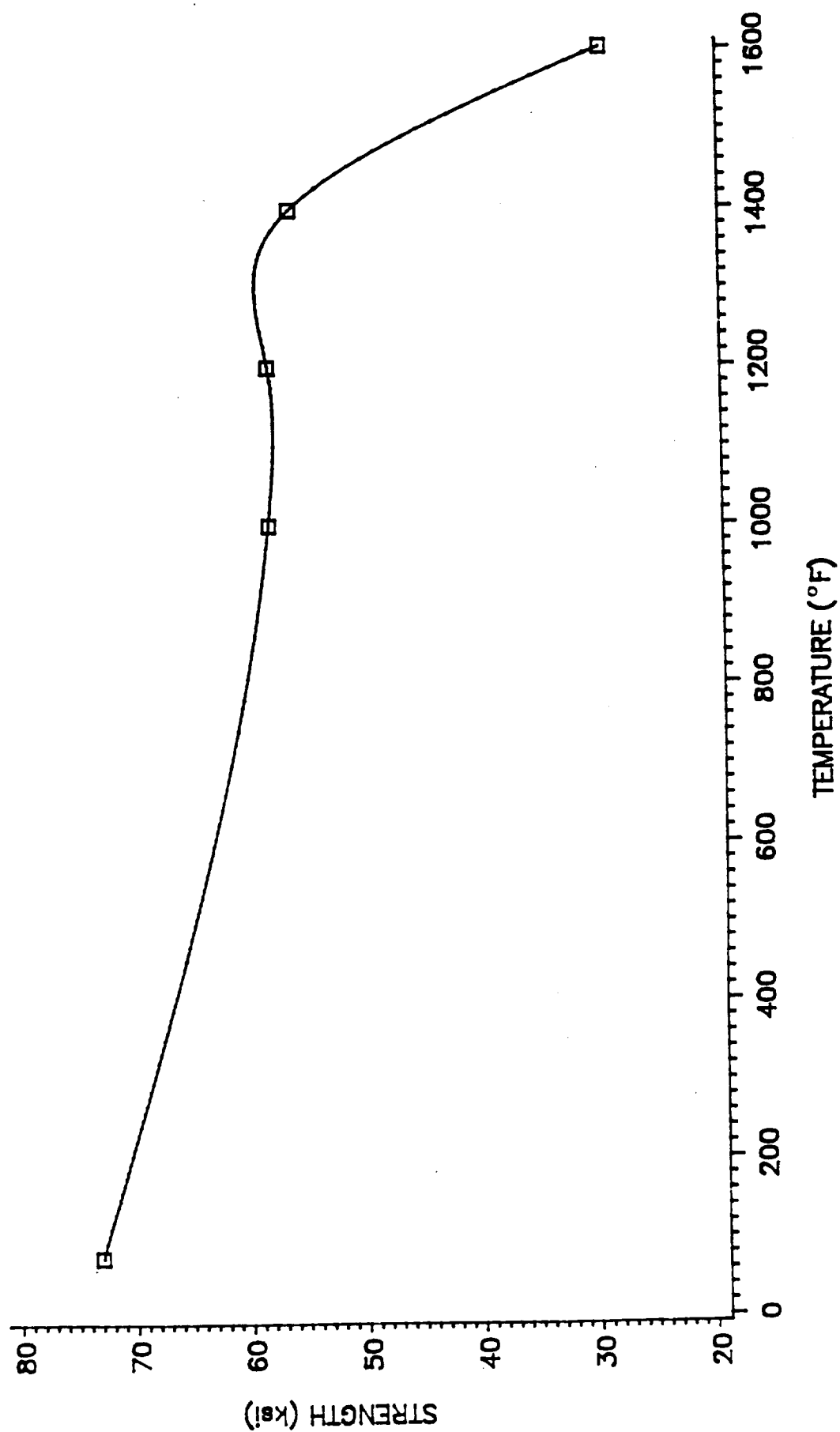
EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR IN-939



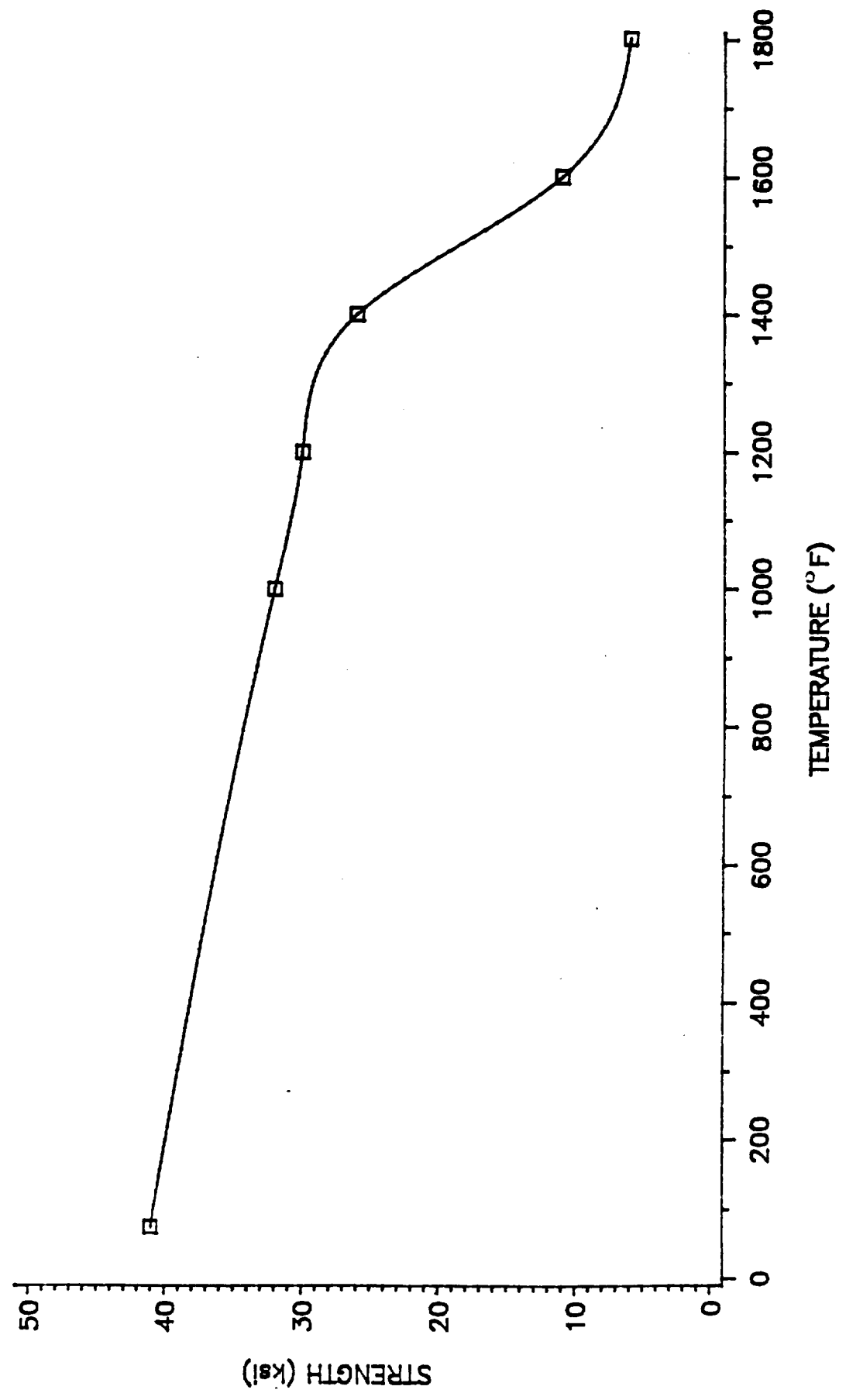
EFFECT OF TEMPERATURE ON YIELD STRENGTH
FOR IN-939



EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR IN-102

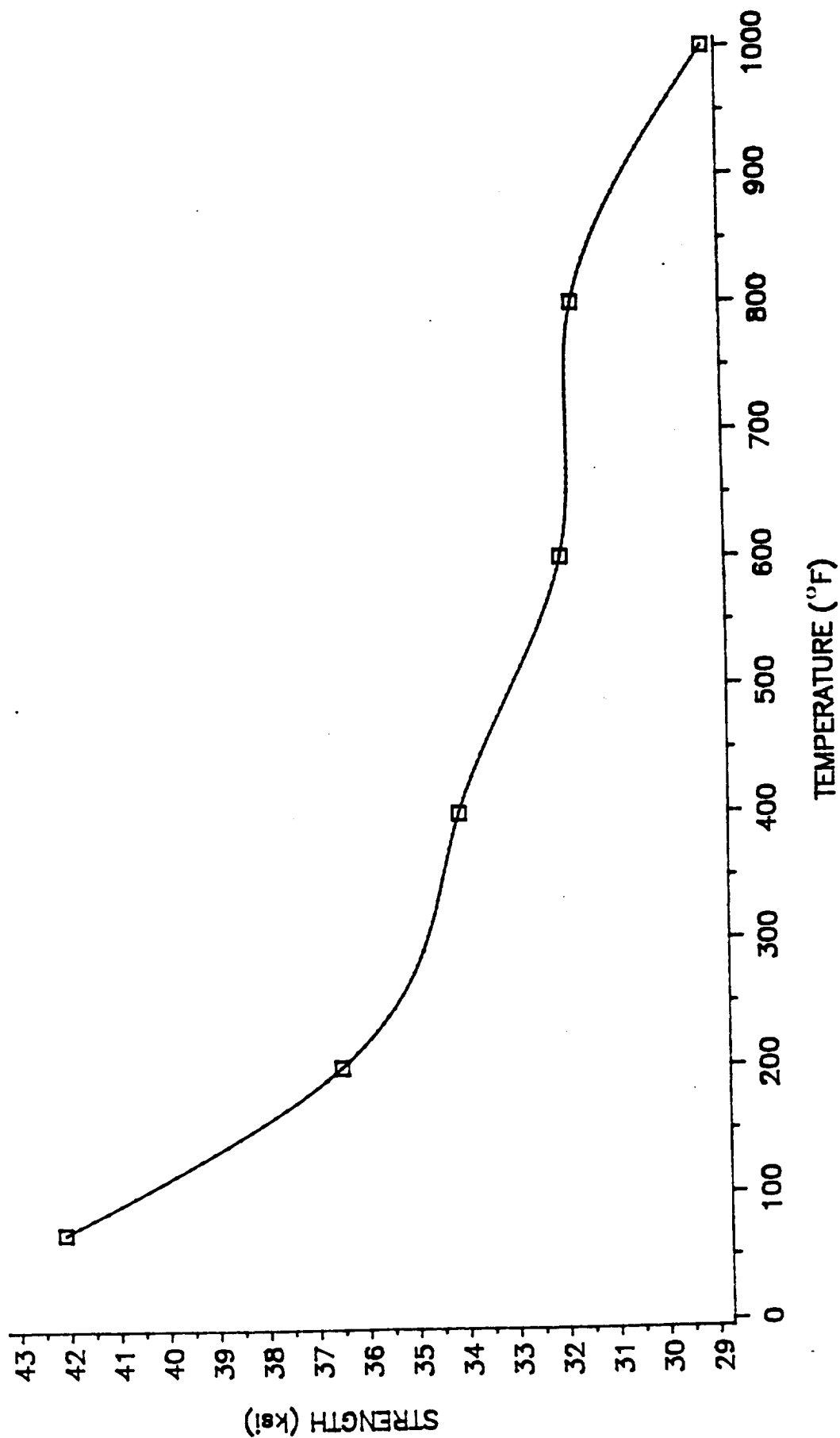


EFFECT OF TEMPERATURE ON YIELD STRENGTH
FOR INCONEL 600



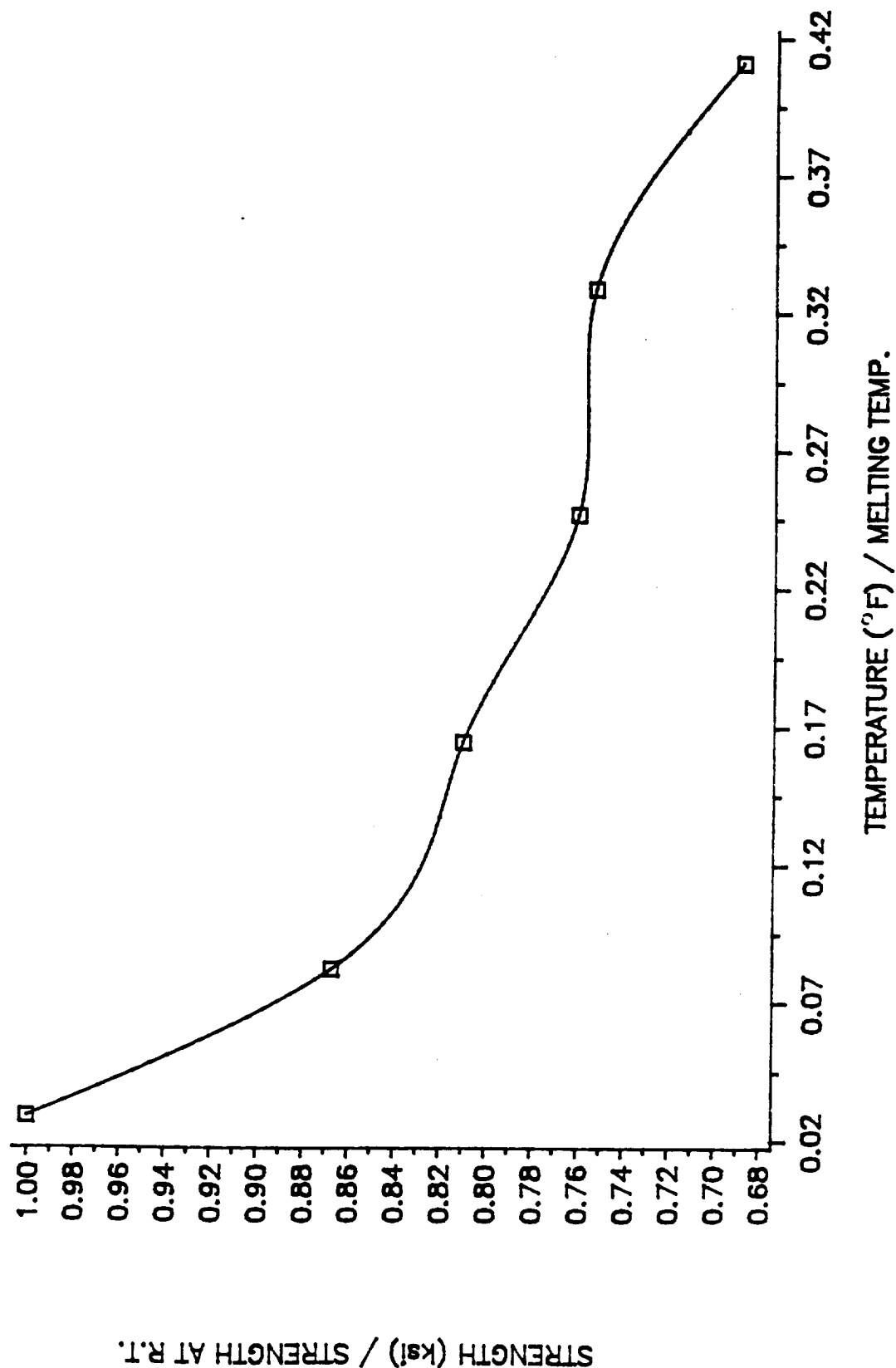
HOT-FINISHED ROD
ANNEALED AT 2000 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 601



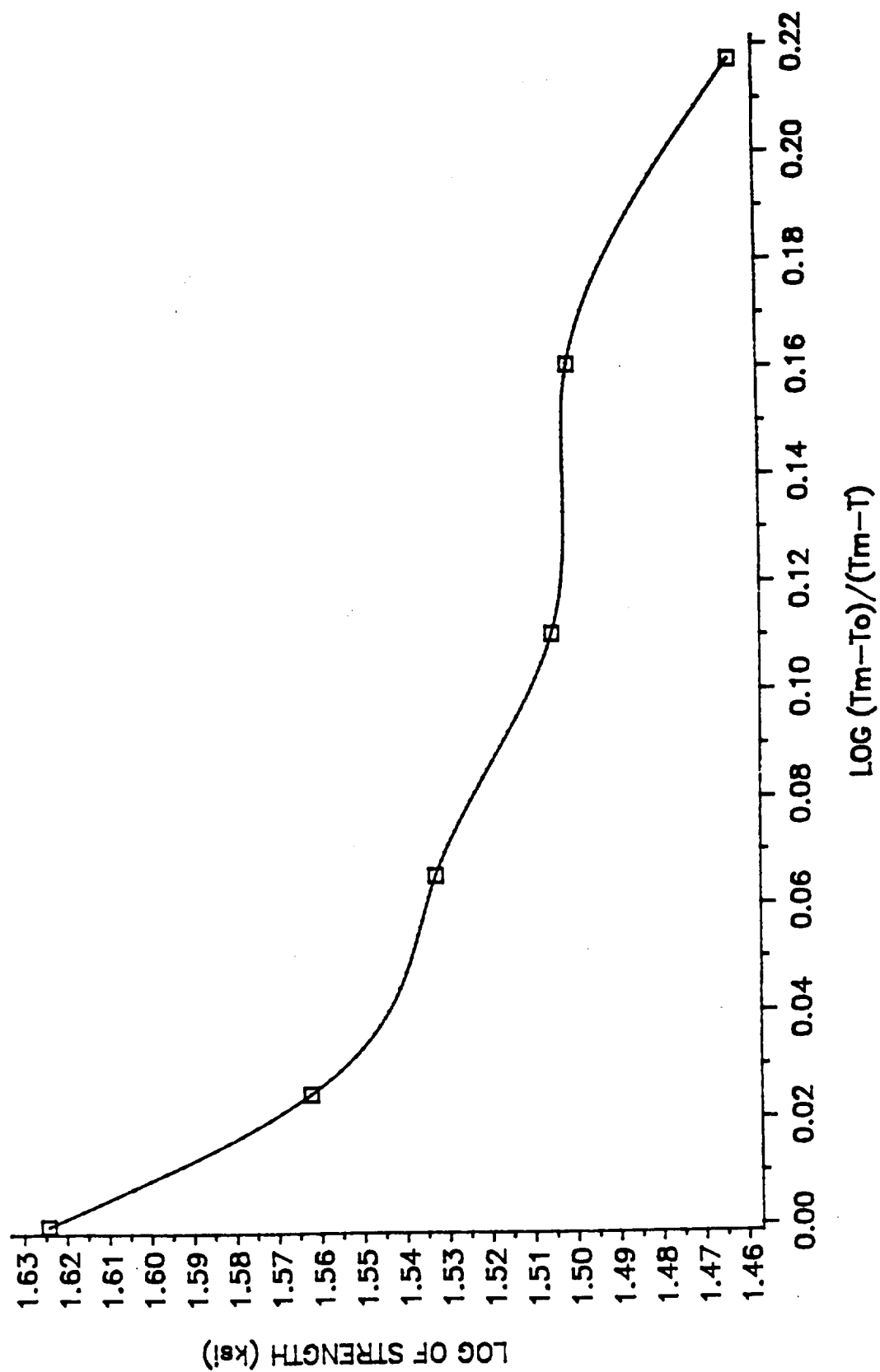
HOT-FINISHED ROD
ANNEALED AT 2000 F
R.T.=70 F, $T_m=2434$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 601



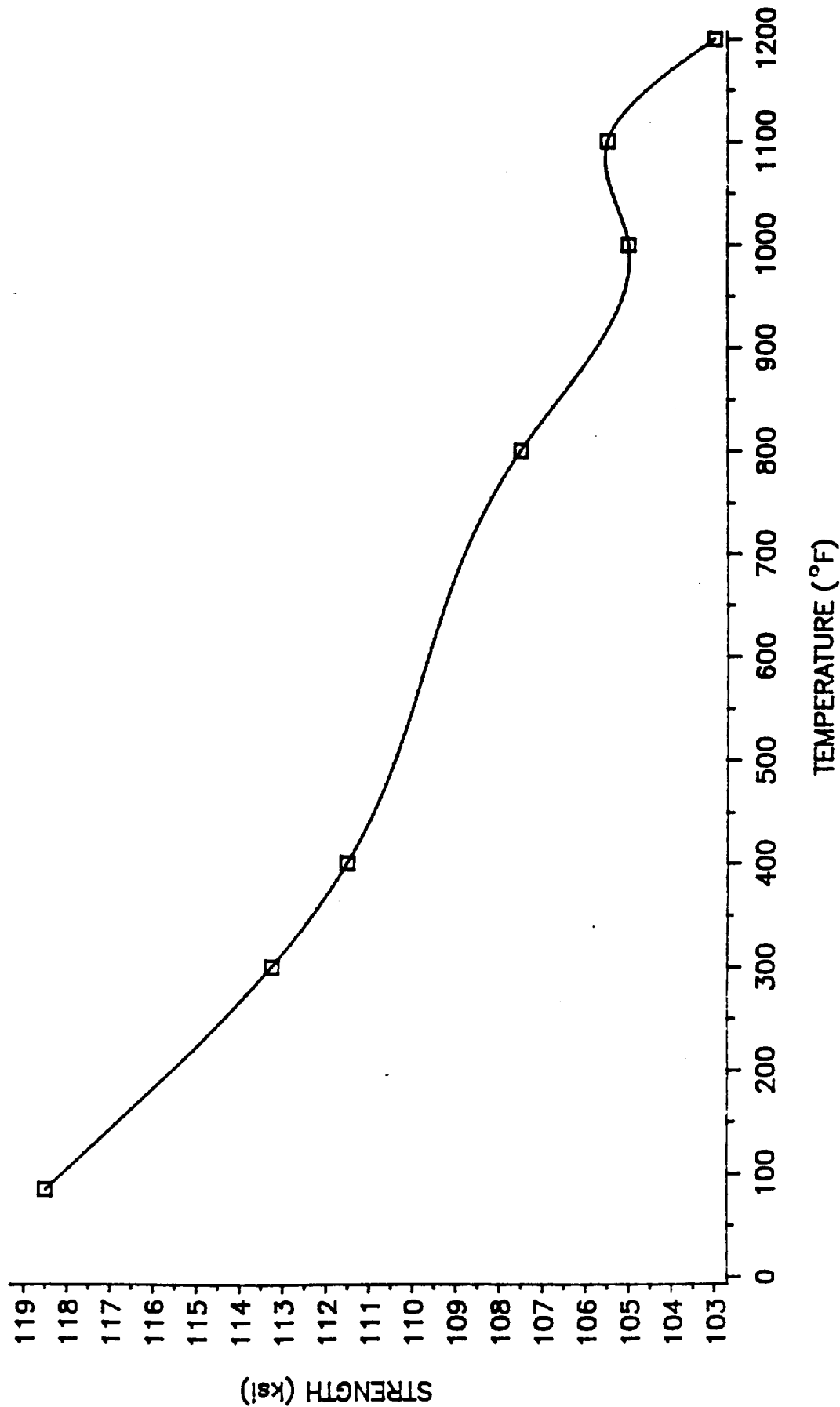
HOT-FINISHED ROD
ANNEALED AT 2000 F
 $T_o=70$ F, $T_m=2434$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL 601



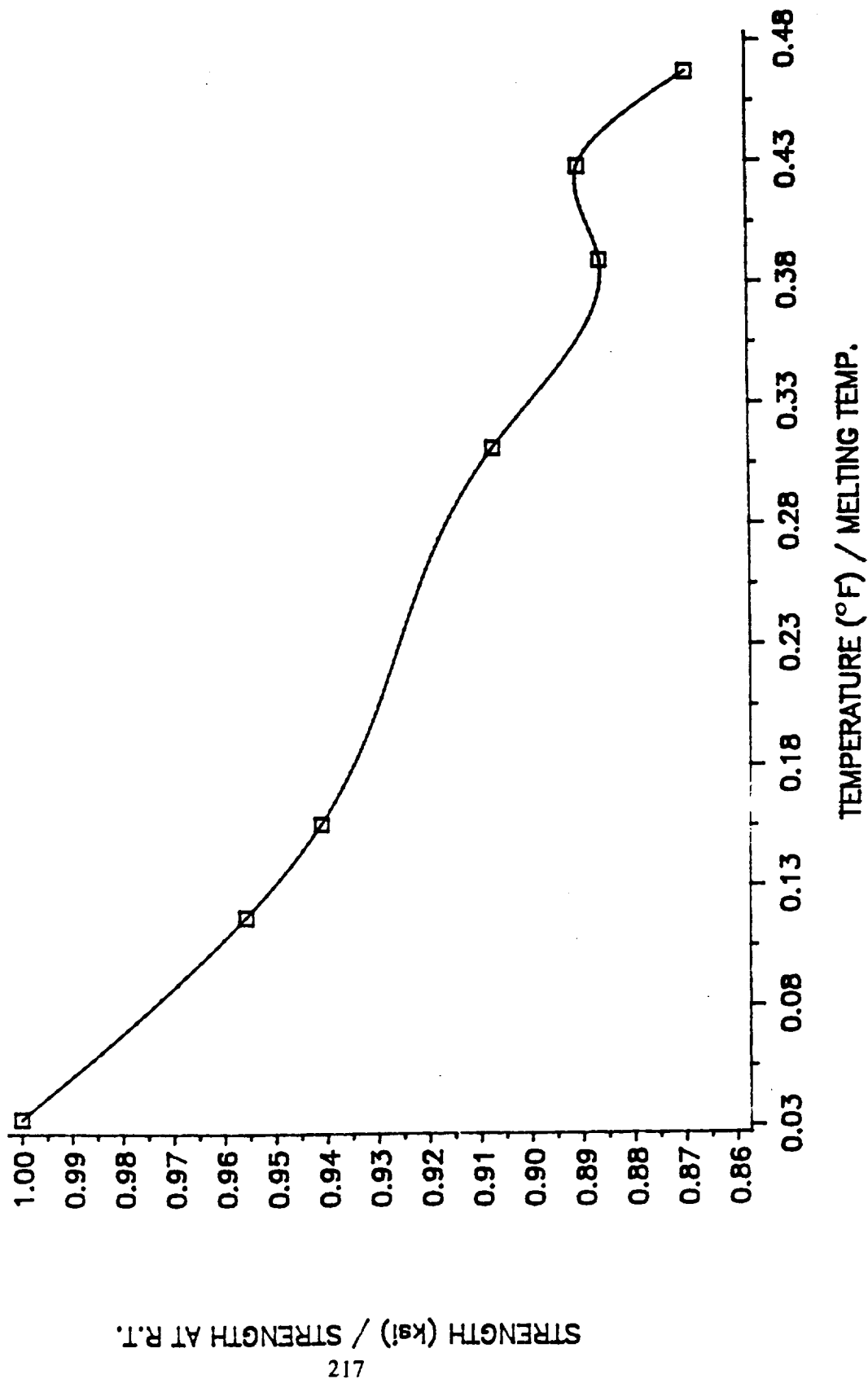
ROLLED 1 3/16" BAR
EQUALIZED AND PRECIPITATION-TREATED
(1625 F/24 HR + 1300 F/20 HR)

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



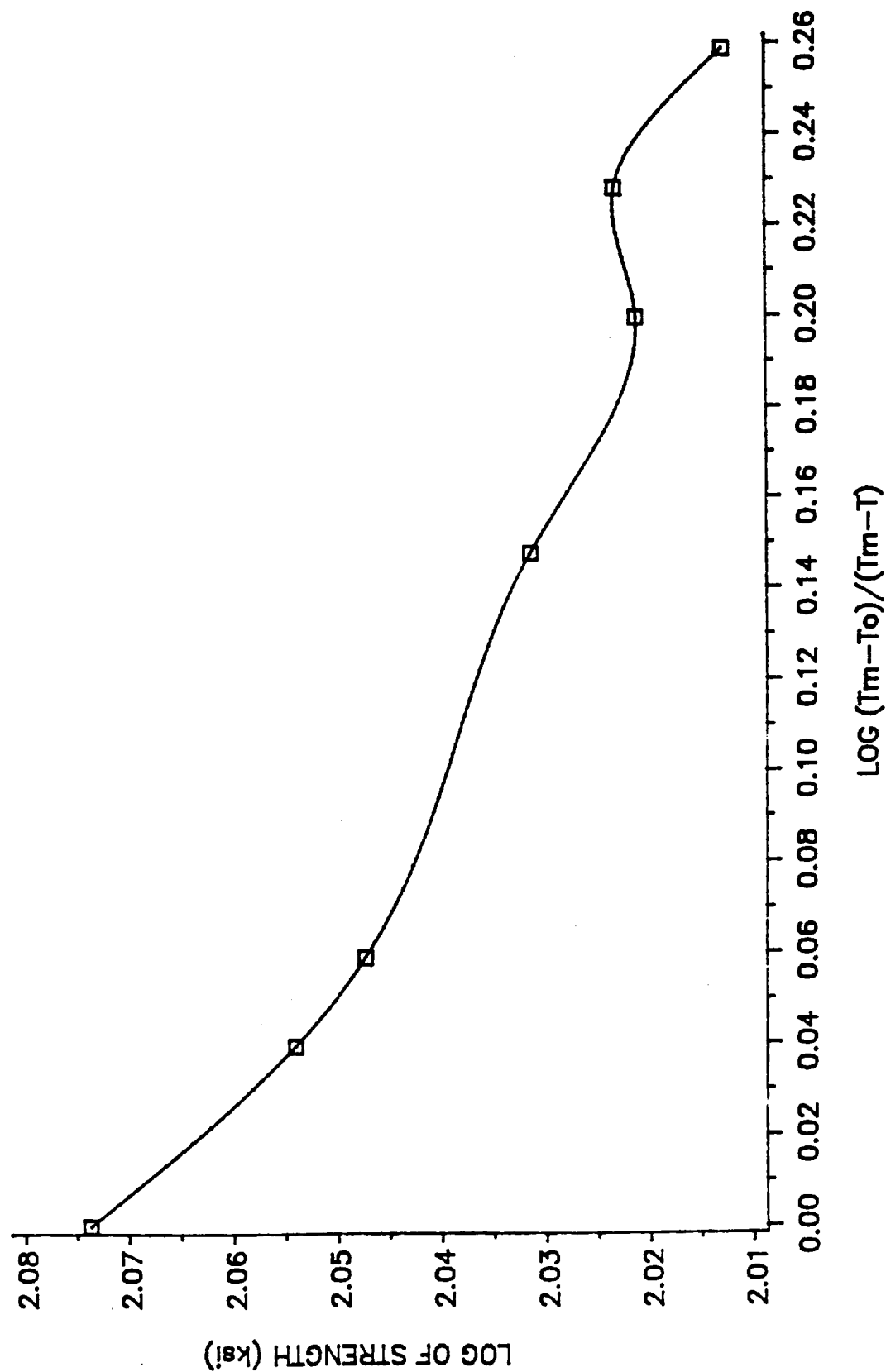
HOT-ROLLED 1 3/16" BAR
EQUALIZED AND PRECIPITATION-TREATED
(R.T.=85 F, T_m=2570 F)

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



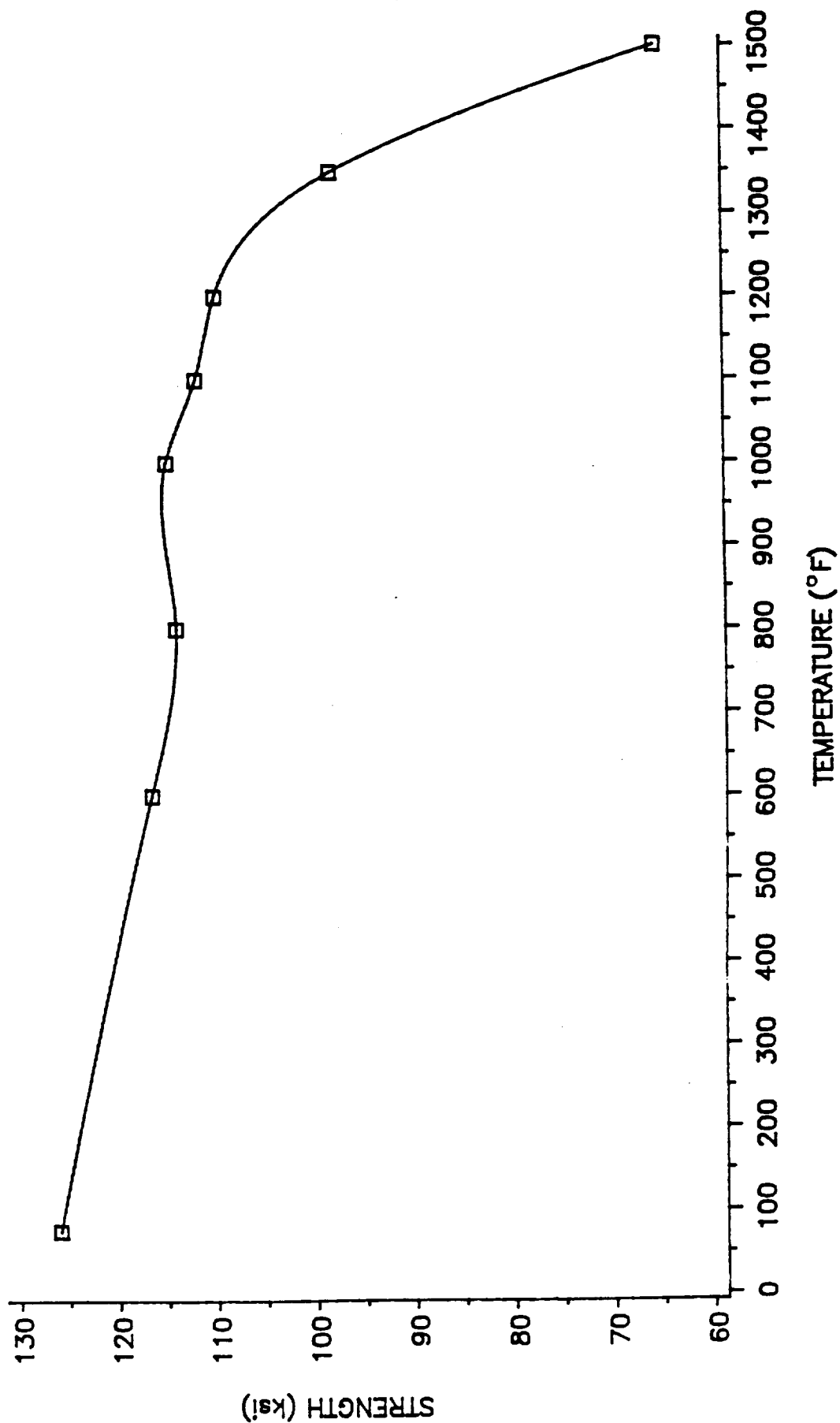
HOT-ROLLED 1 3/16" BAR
EQUALIZED AND PRECIPITATION-TREATED
($T_0=85$ F, $T_m=2570$ F)

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



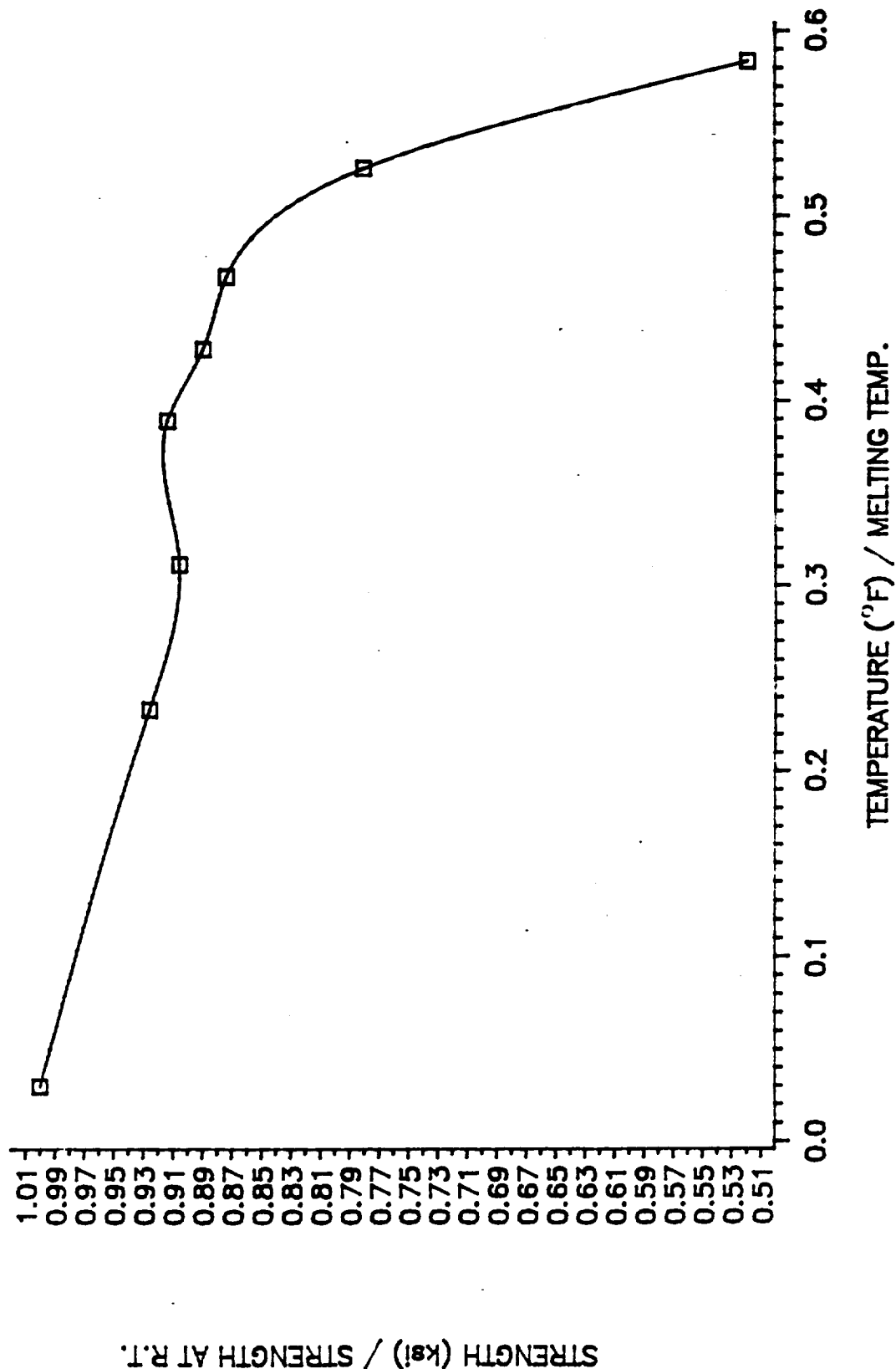
HOT-ROLLED ROUND
EQUALIZED AND PRECIPITATION--TREATED

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



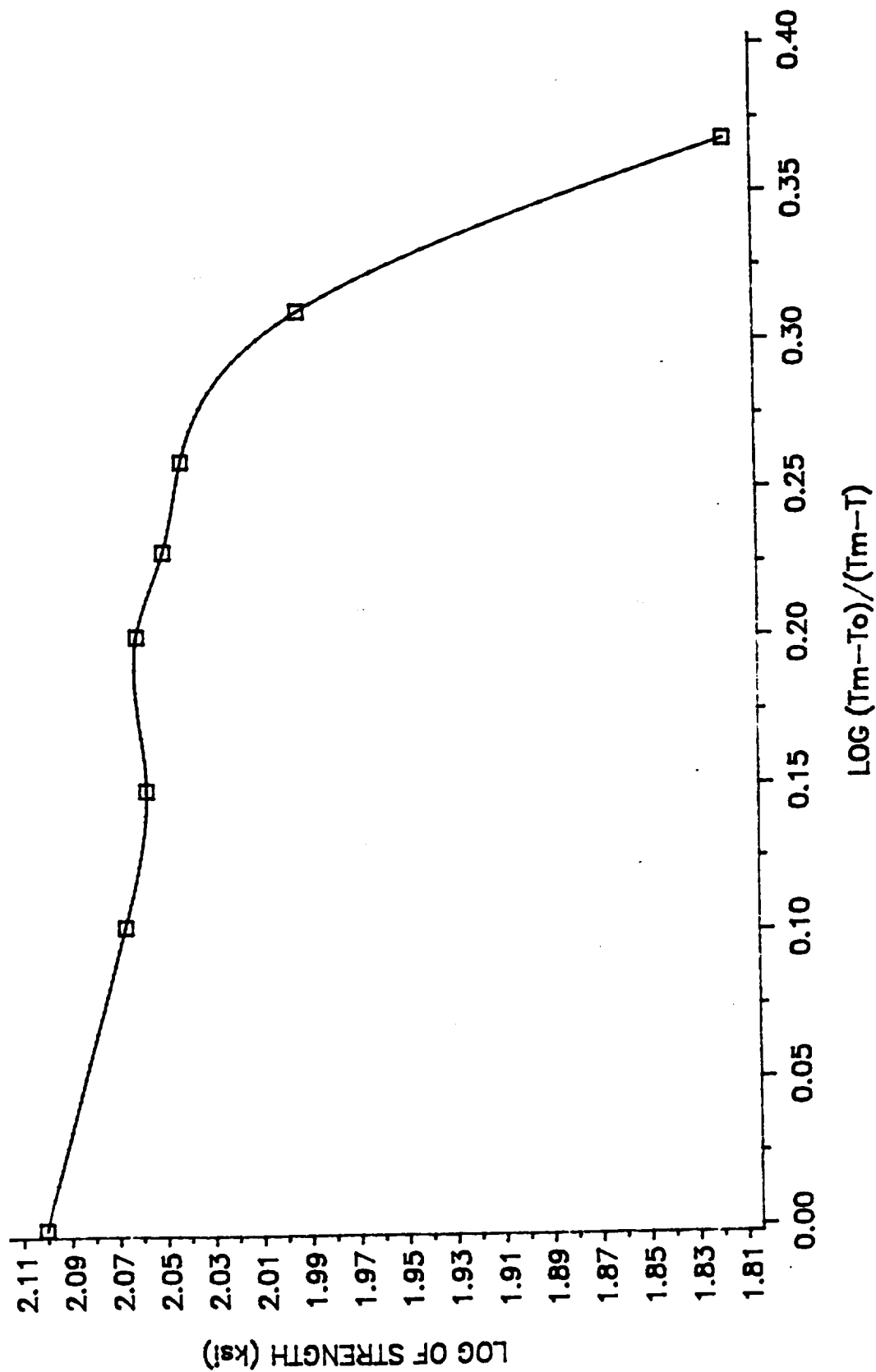
HOT-ROLLED ROUND
EQUALIZED AND PRECIPITATION-TREATED
R.T.=75 F, T_m=2570 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



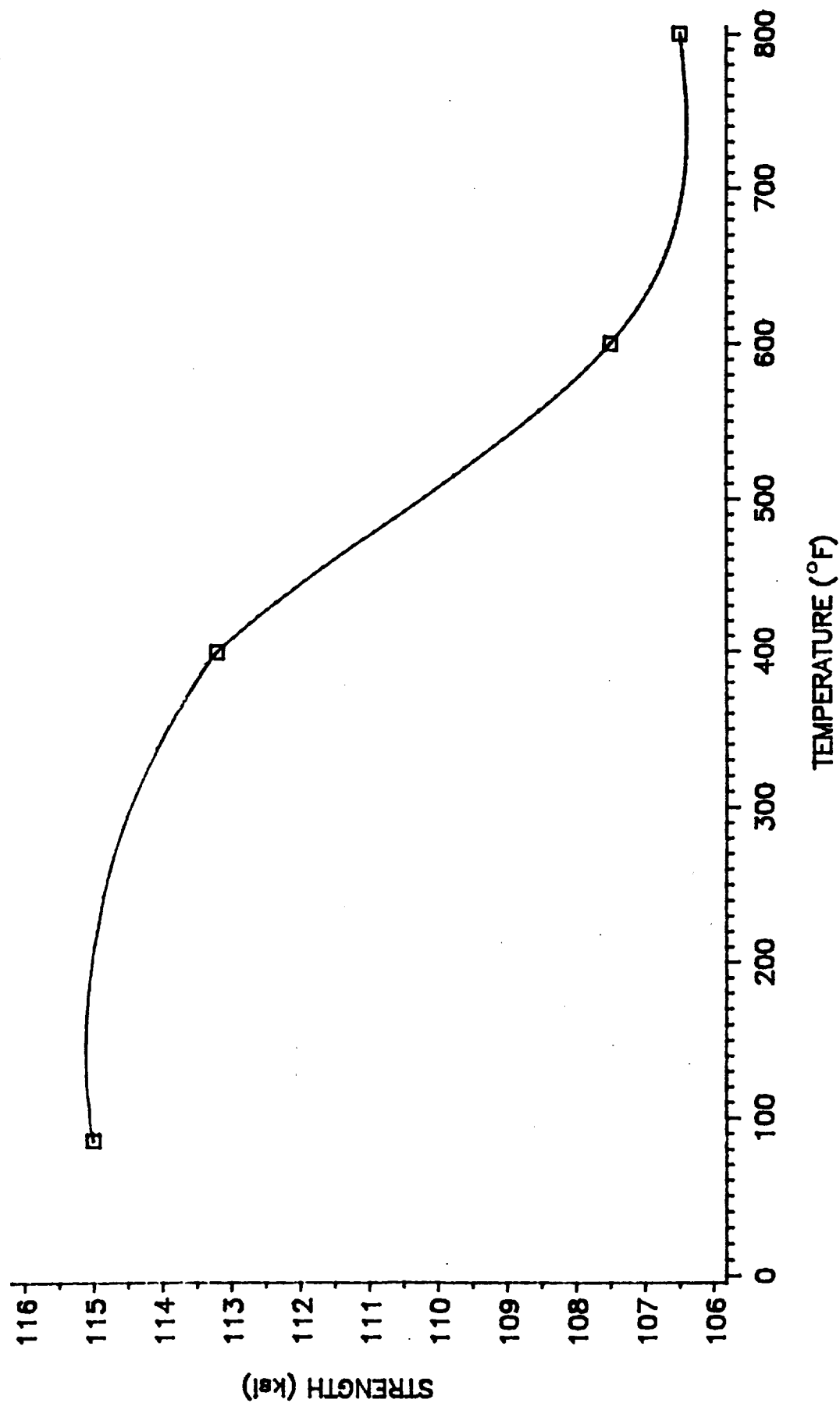
HOT-ROLLED ROUND
EQUALIZED AND PRECIPITATION-TREATED
 $T_0=75^\circ\text{F}$, $T_m=2570^\circ\text{F}$

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



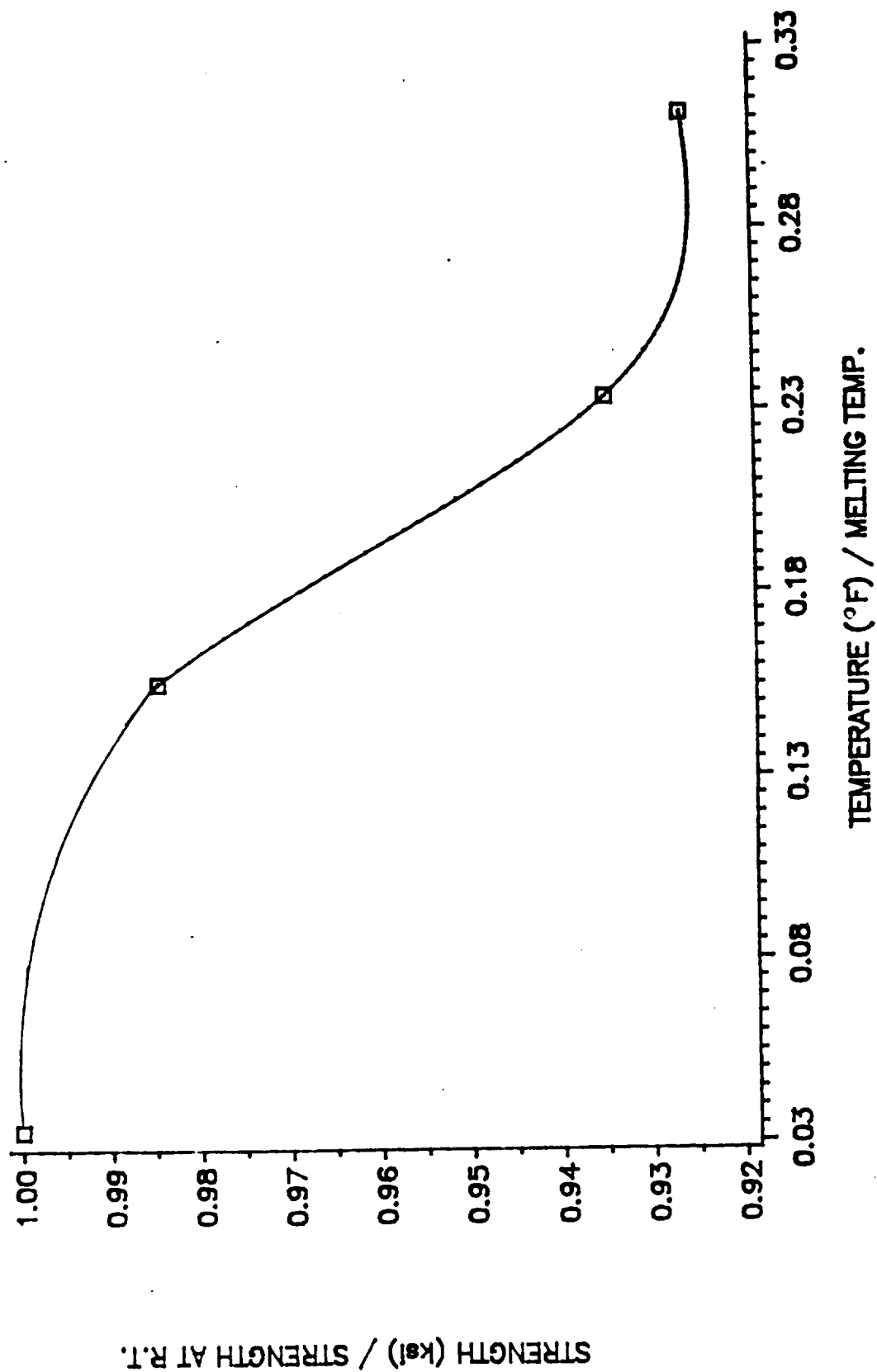
HOT-ROLLED ROUND
SOLUTION-TREATED
(1800 F/1 hr)

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



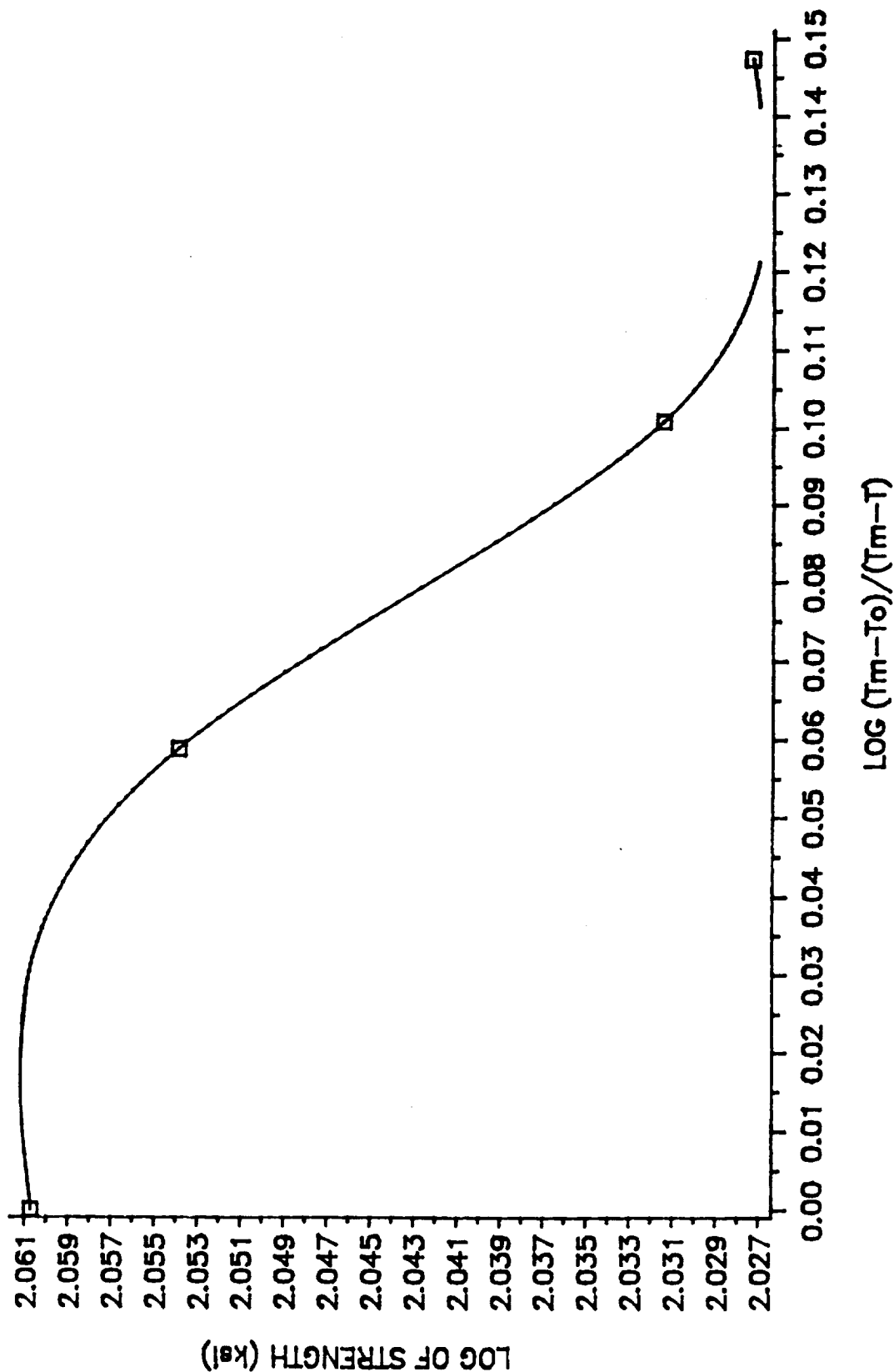
HOT-ROLLED ROUND
SOLUTION-TREATED
R.T.=85 F, T_m=2570 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



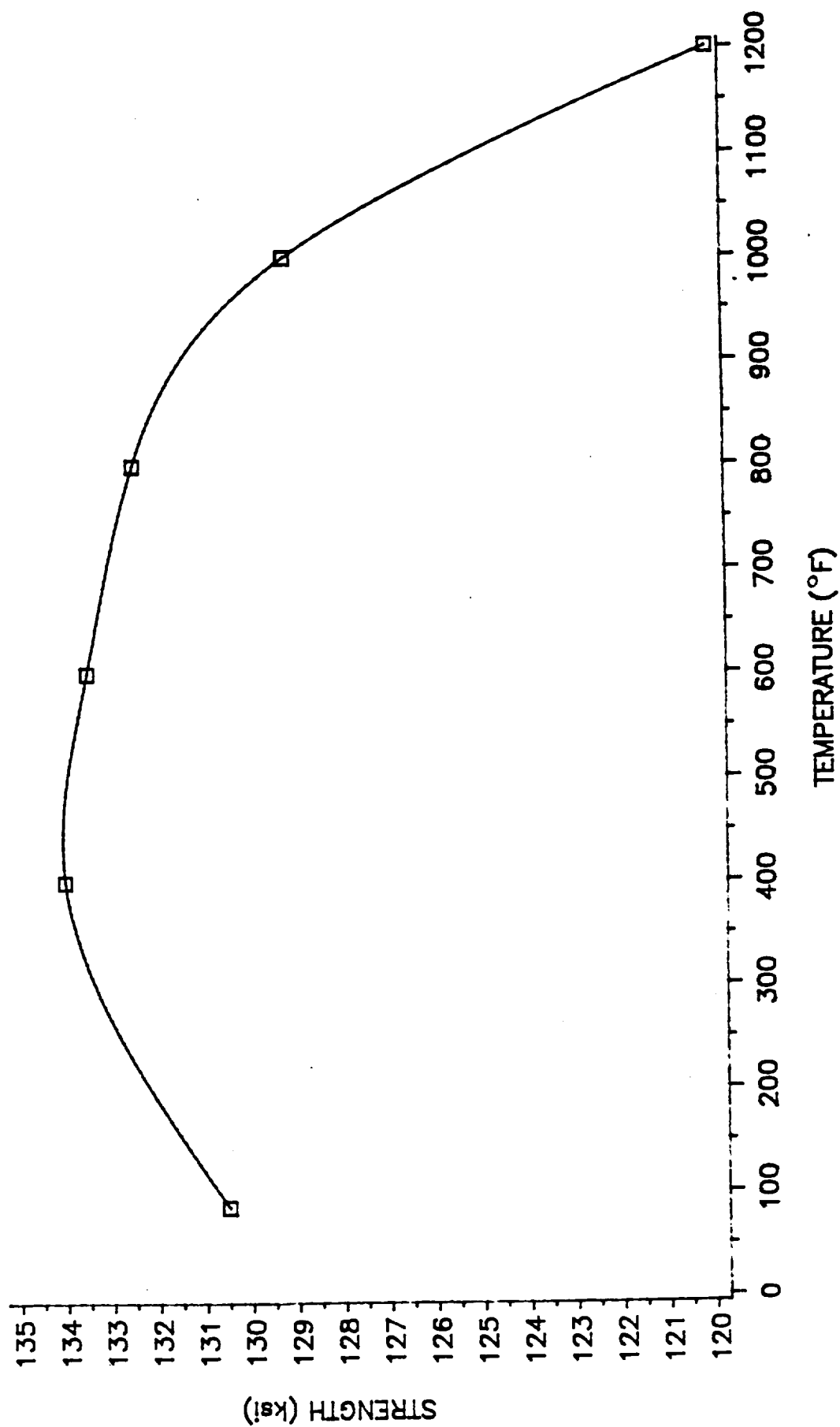
HOT-ROLLED ROUND
SOLUTION-TREATED
 $T_0=85$ F, $T_m=2570$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



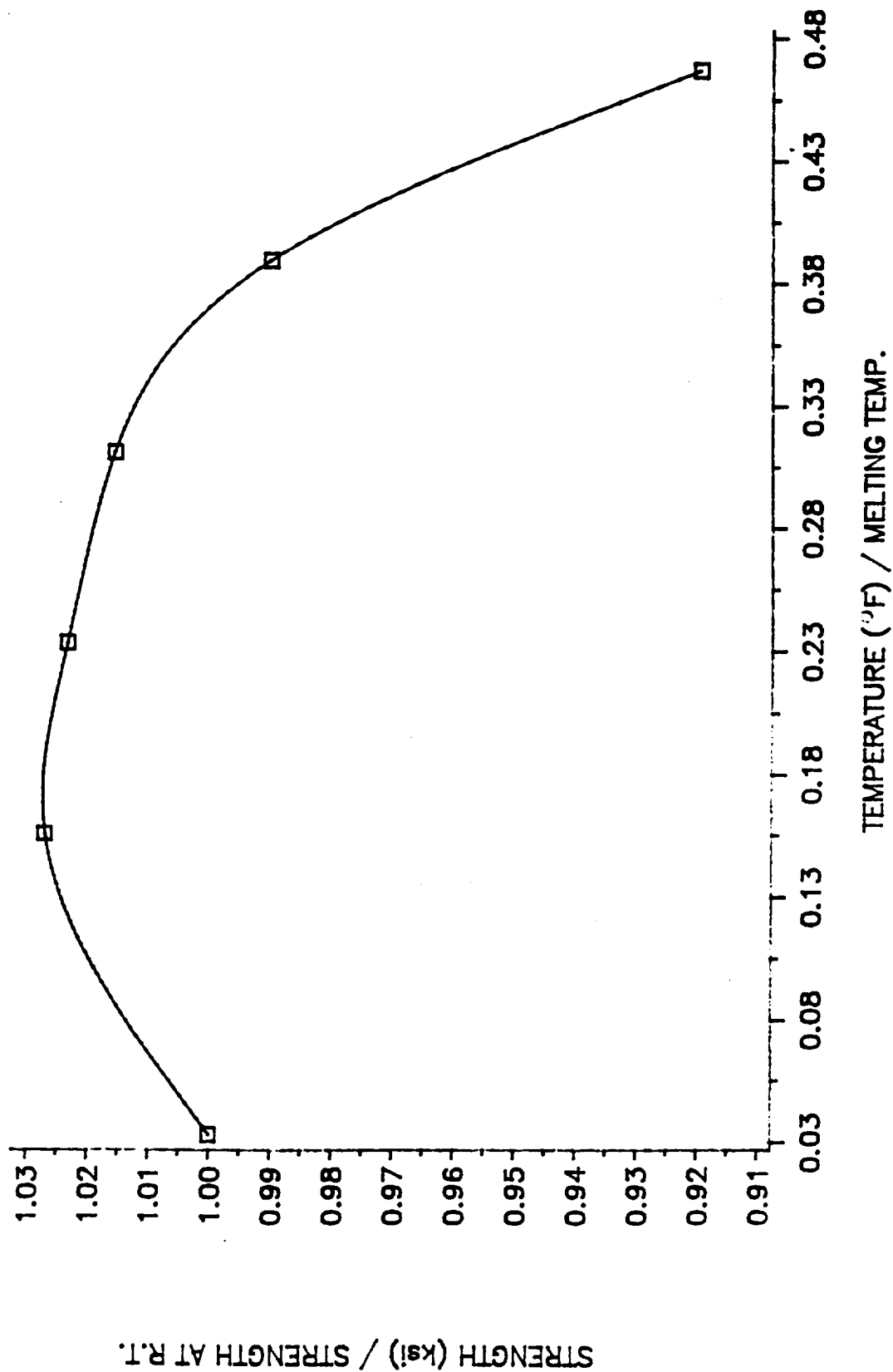
HOT-ROLLED 1" BAR
SOLUTION AND PRECIPITATION--TREATED

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



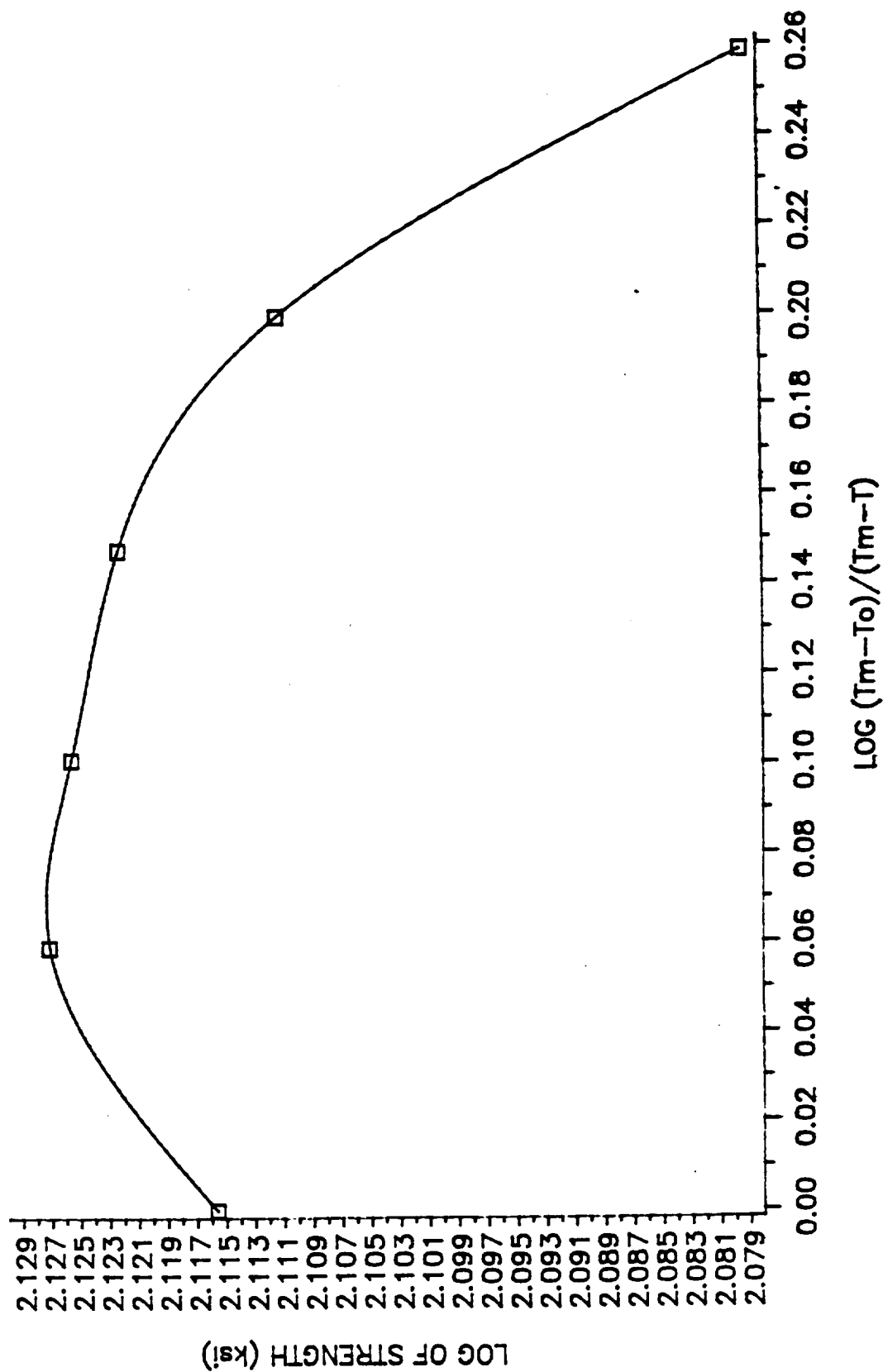
HOT-ROLLED 1" BAR
SOLUTION AND PRECIPITATION-TREATED
R.T.=85 F, T_m=2570 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



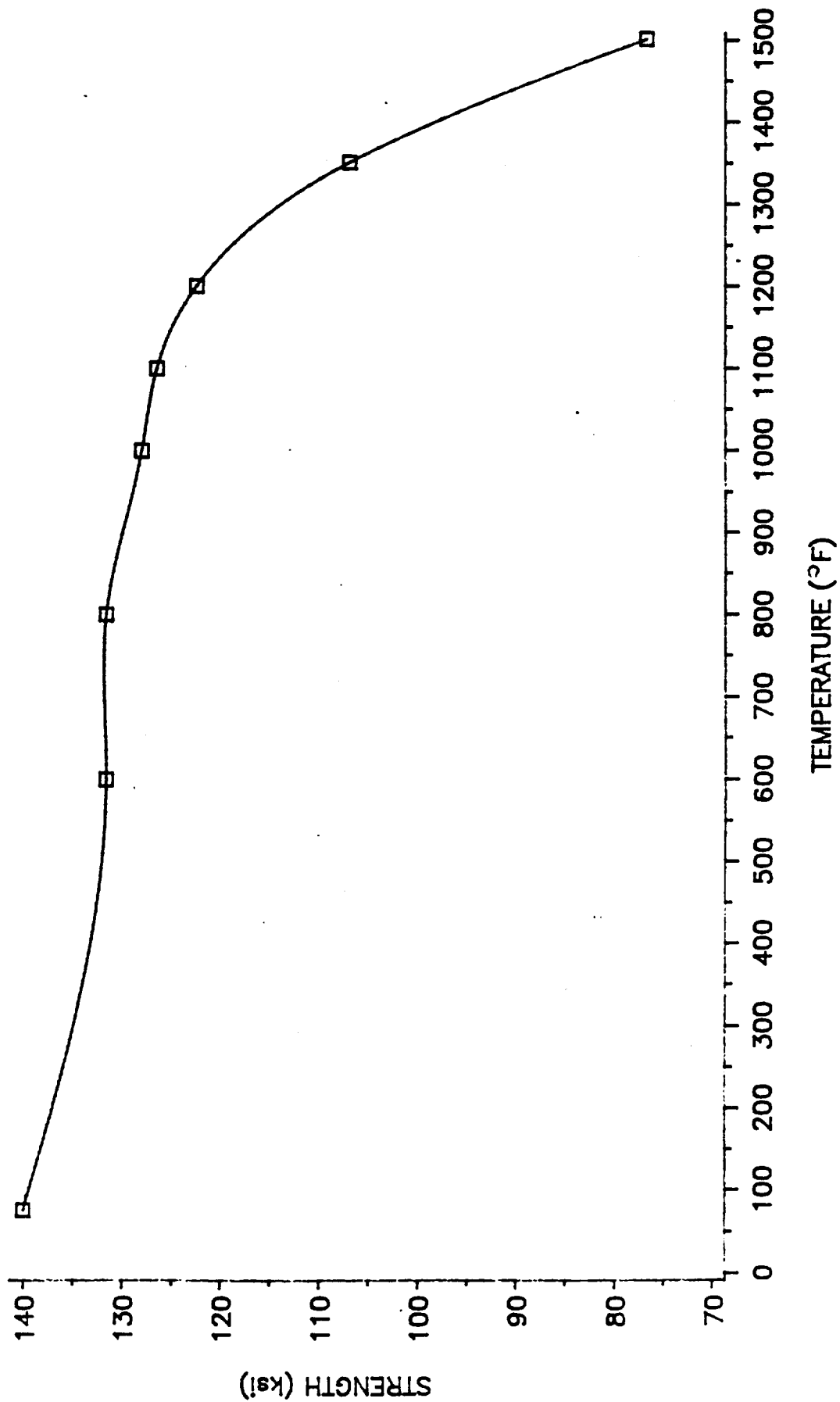
HOT-ROLLED 1" BAR
SOLUTION AND PRECIPITATION-TREATED
To=85 F, Tm=2570 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750



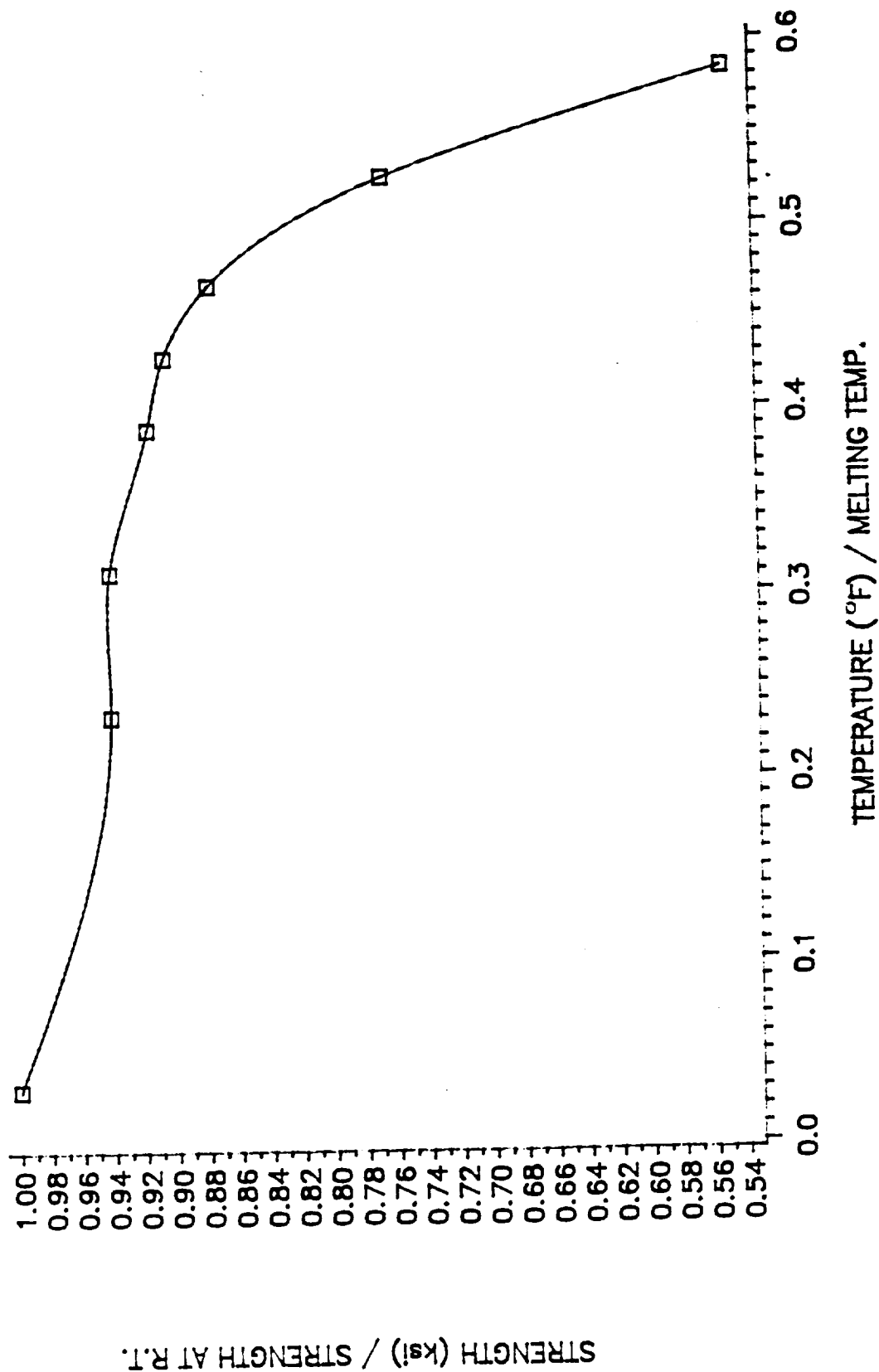
HOT-ROLLED ROUND
SOLUTION AND PRECIPITATION-TREATED

EFFECT OF TEMPERATURE ON YIELD STRENGTH
FOR INCONEL X-750



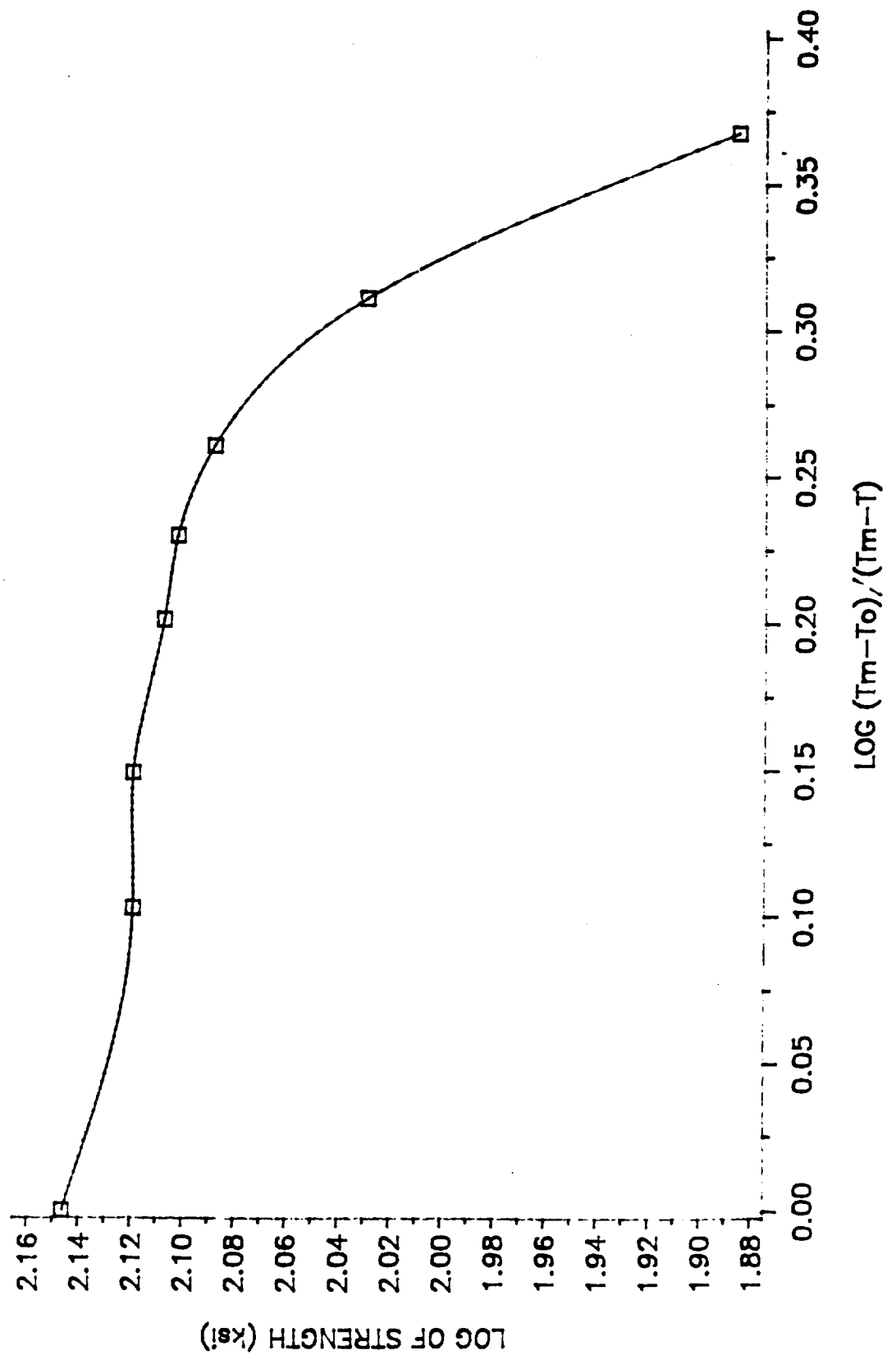
HOT-ROLLED ROUND
SOLUTION AND PRECIPITATION-TREATED
R.T.=75 F, T_m=2570 F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750

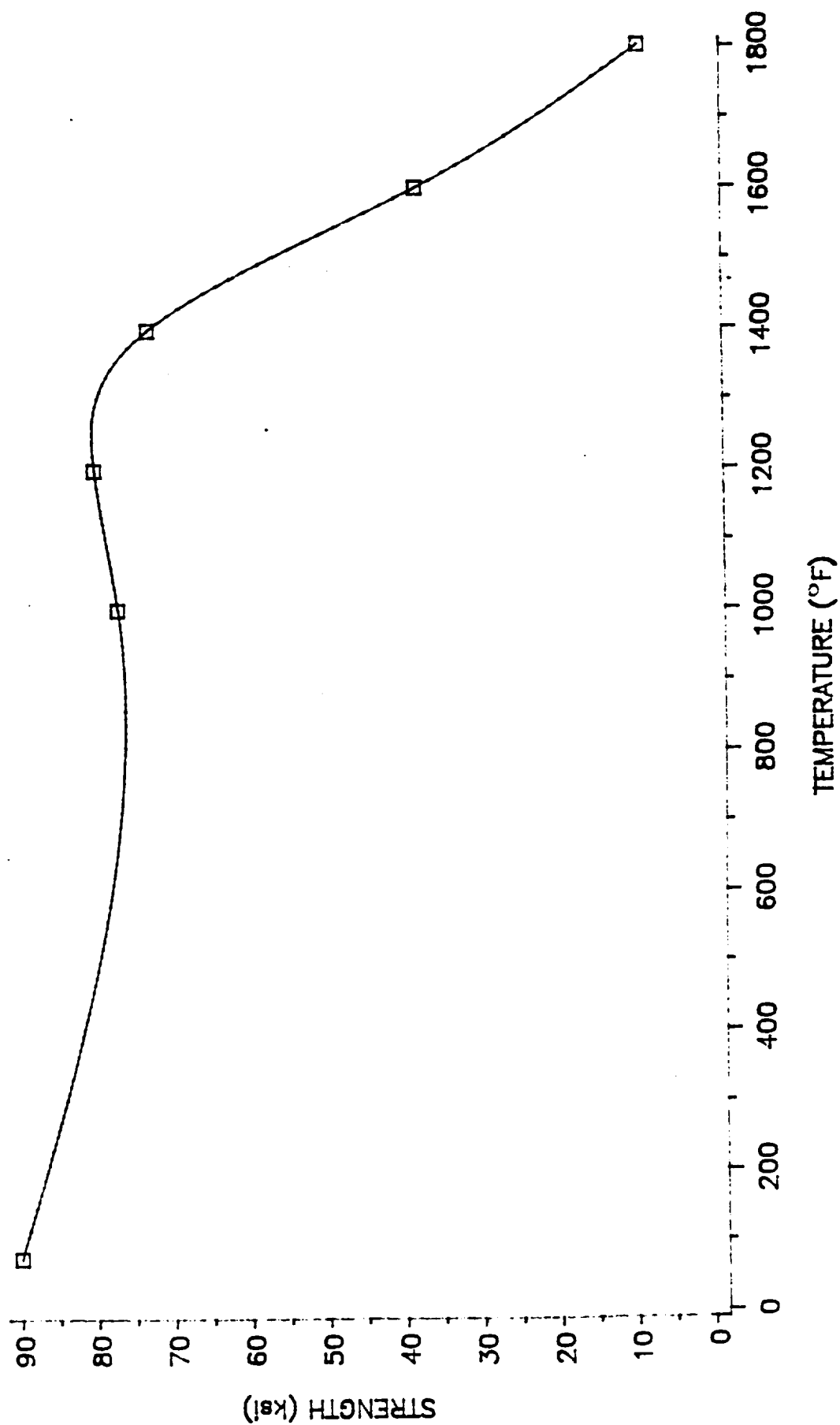


HOT-ROLLED ROUND
SOLUTION AND PRECIPITATION-TREATED
 $T_0=75$ F, $T_m=2570$ F

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR INCONEL X-750

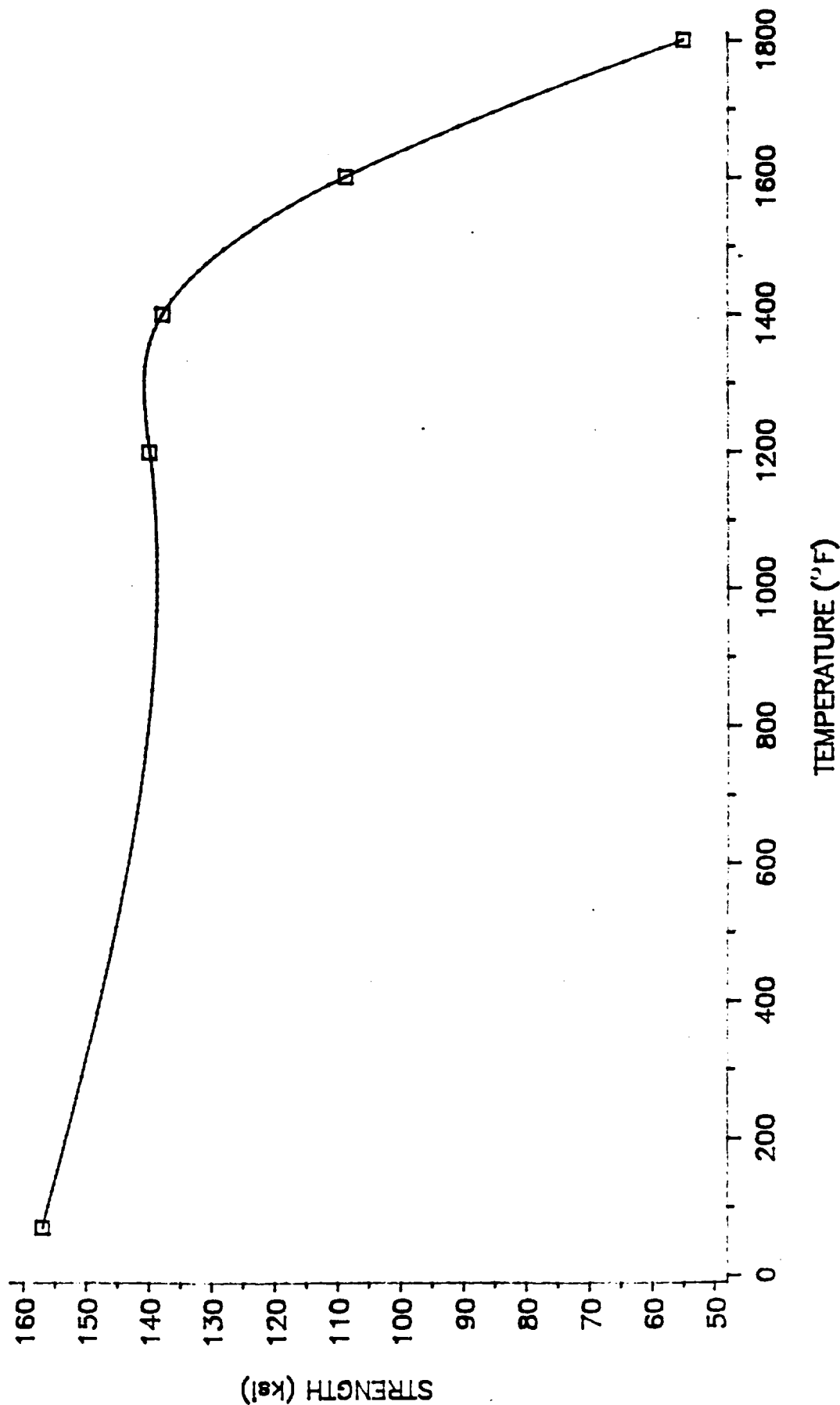


EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR NIMONIC 80A

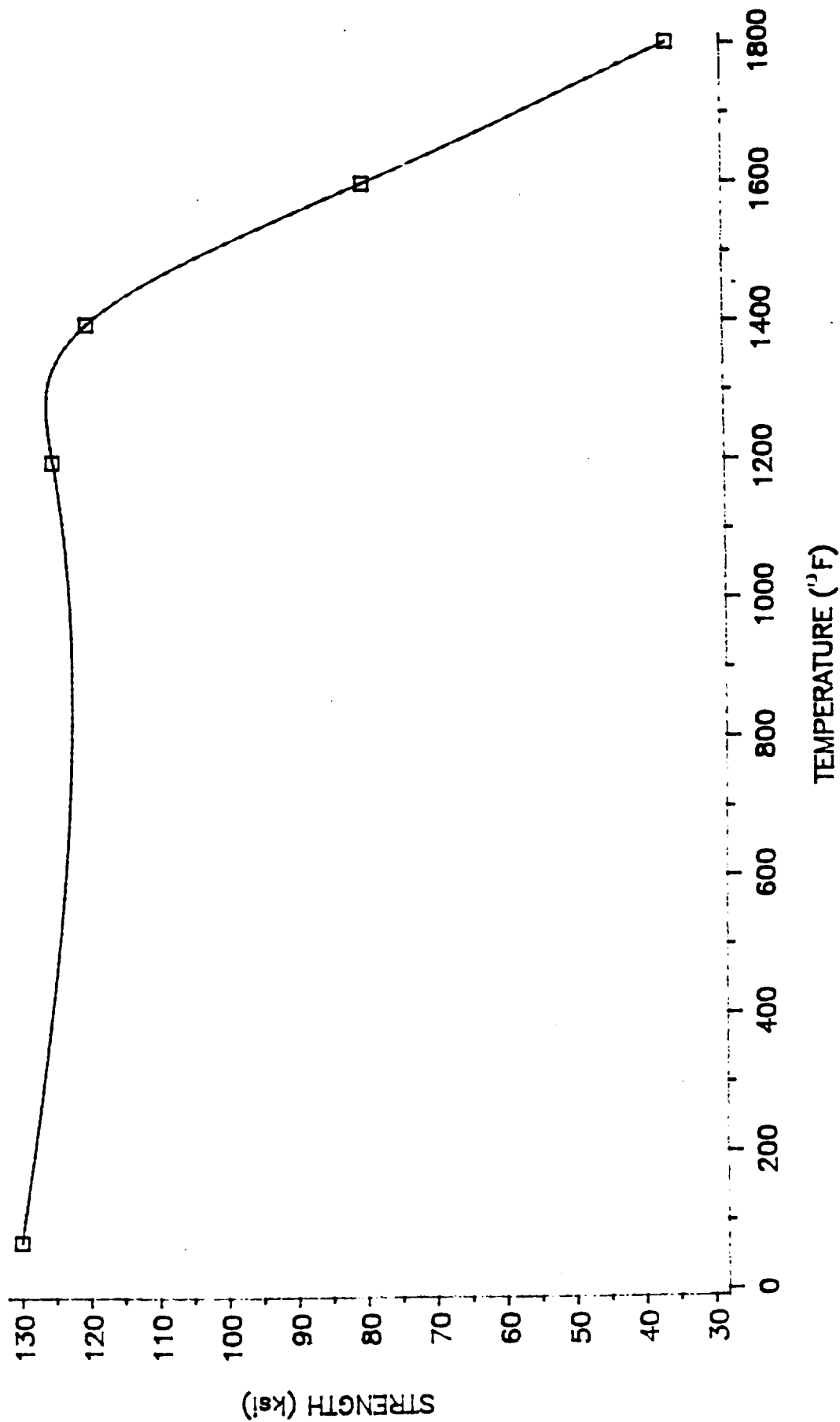


HEAT-TREATED
CAST ALLOY

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR MAR-M421

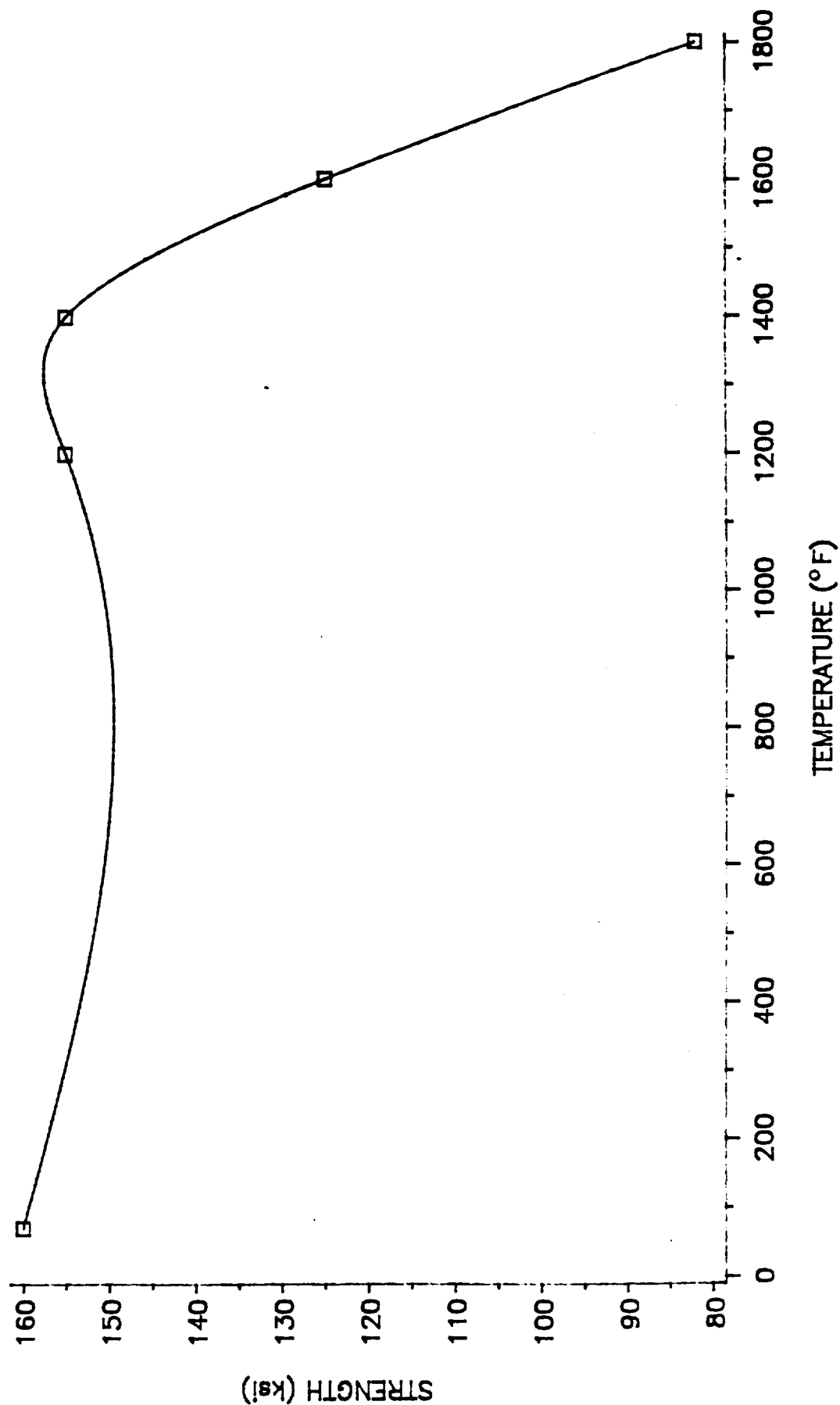


EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR MAR-M421



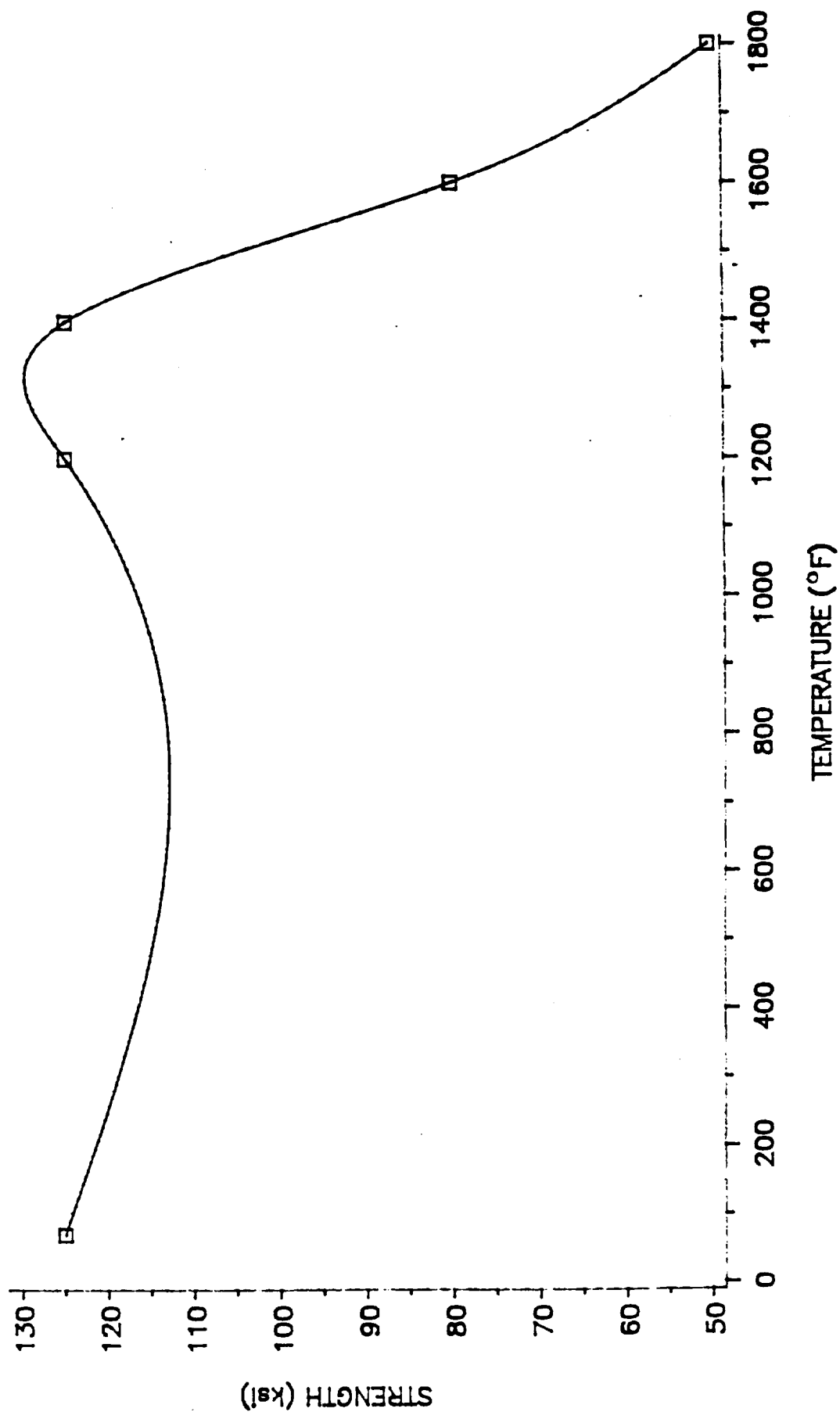
1500 F/50/AC
CAST ALLOY

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR MM-006



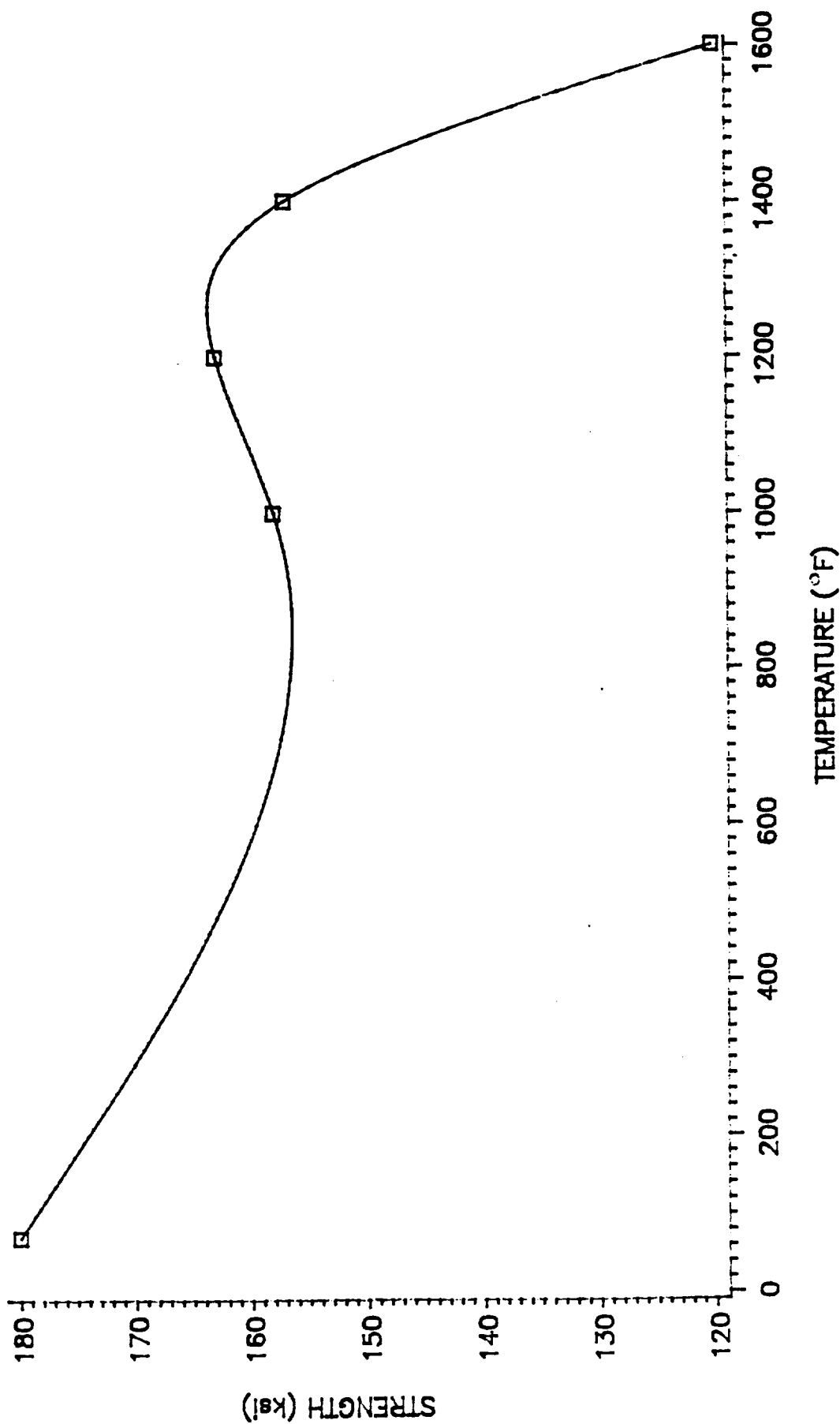
1500 F/50/AC
CAST ALLOY

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR MM-006



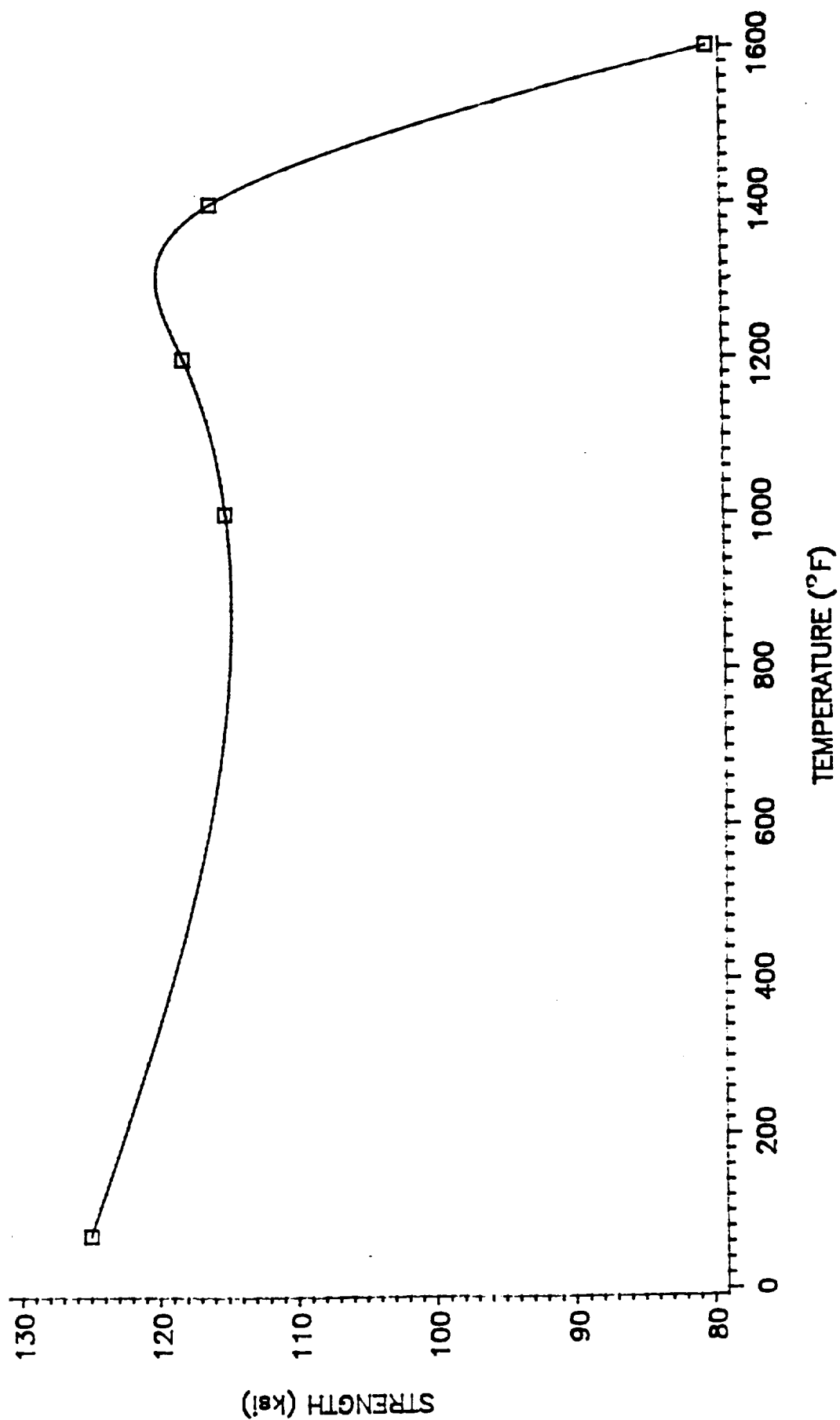
HEAT-TREATED BAR
WROUGHT ALLOY

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR NIMONIC 115



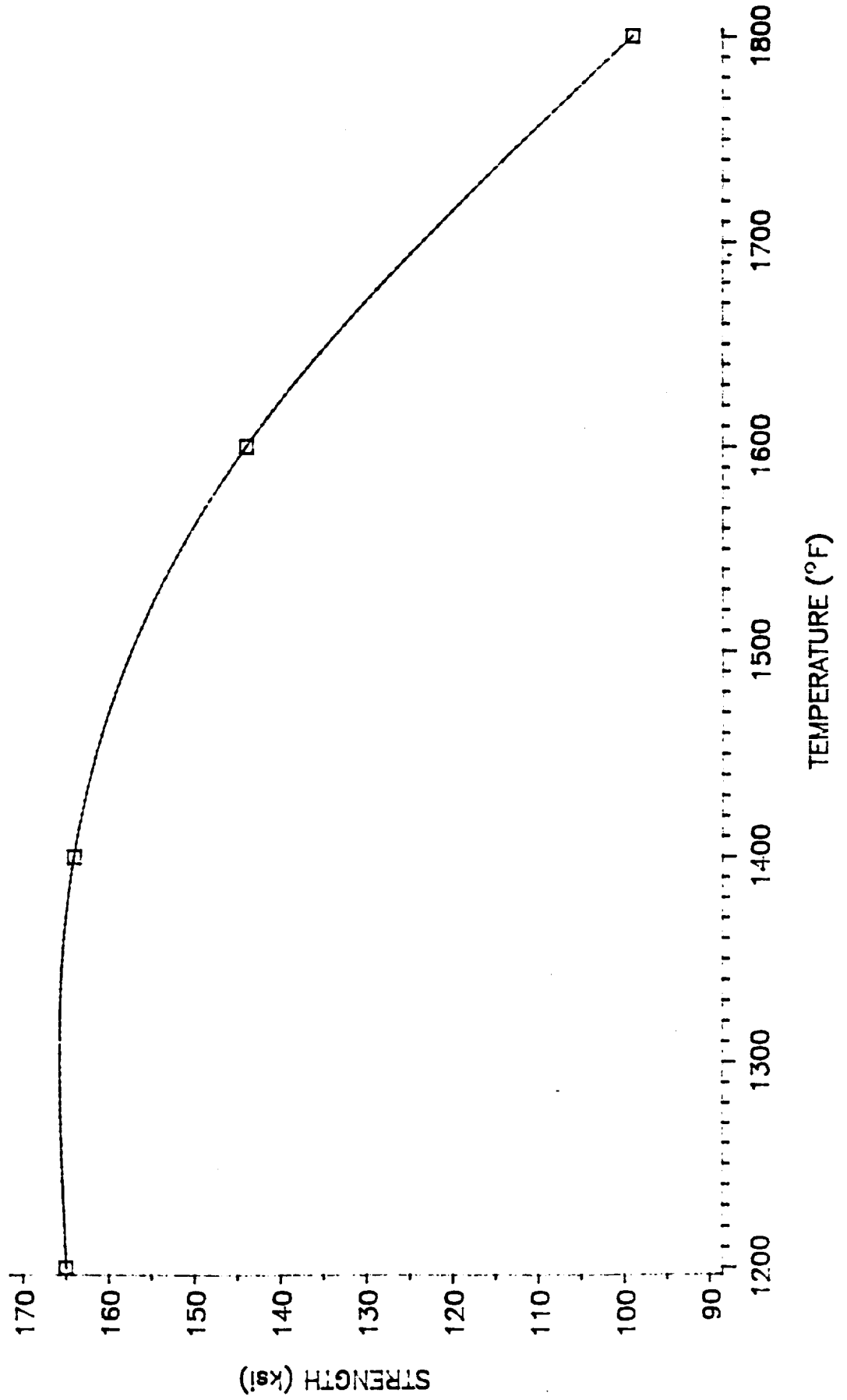
HEAT-TREATED BAR
WROUGHT ALLOY

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR NIMONIC 115

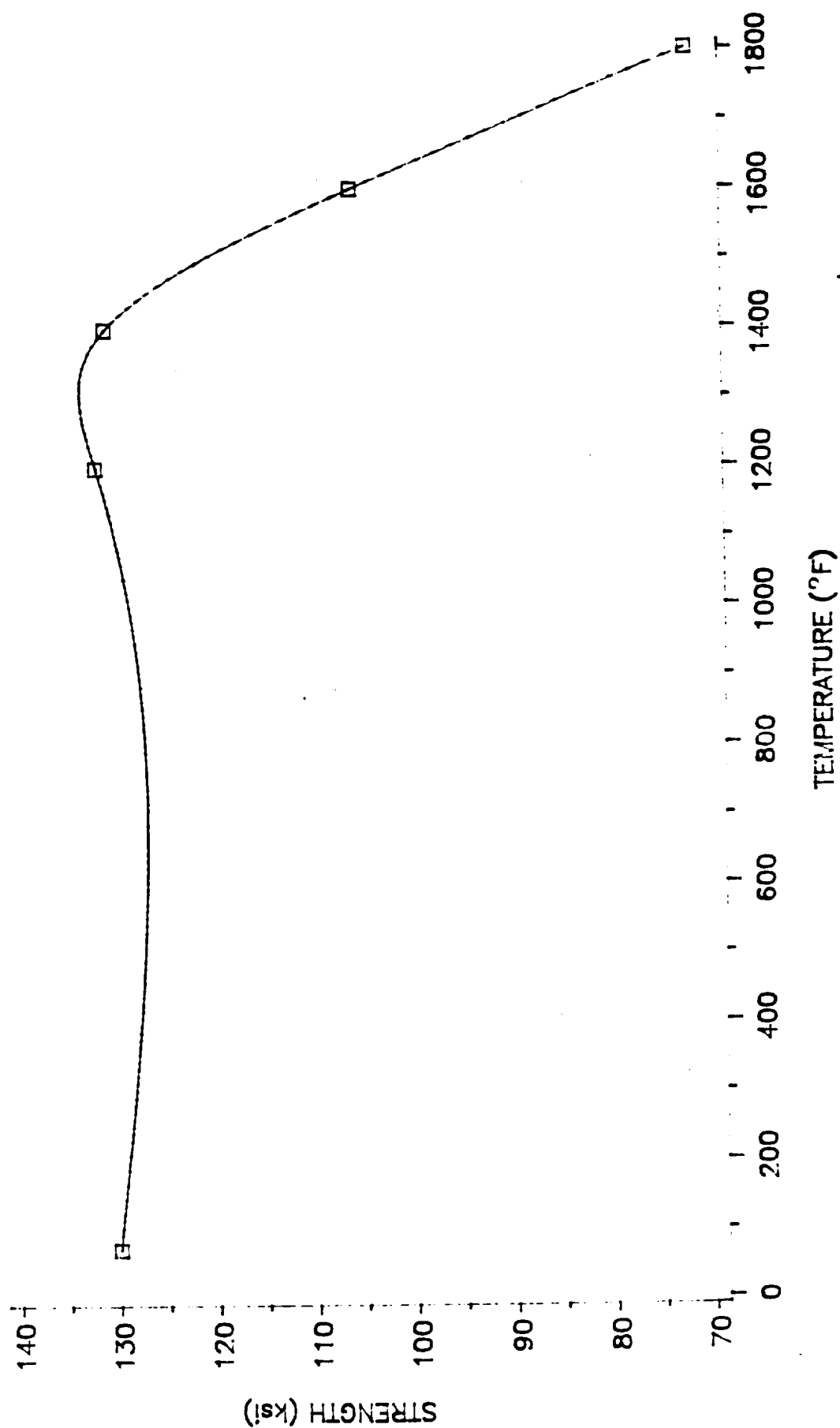


2350 F / 4/AC+1975 F / 4/AC+
1600 F / 32/AC

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR PWA 1480 SC

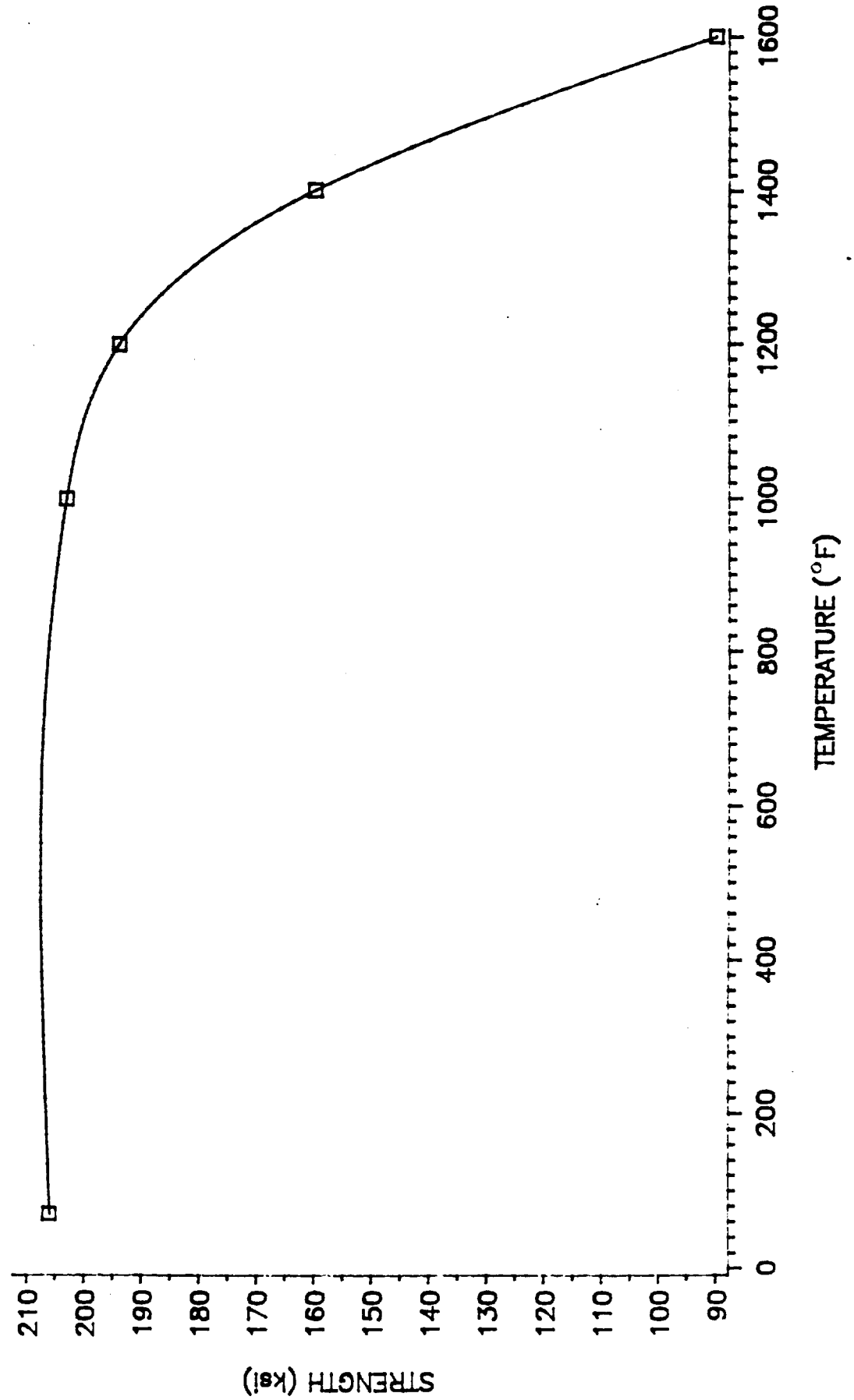


EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR PWA 1480 SC



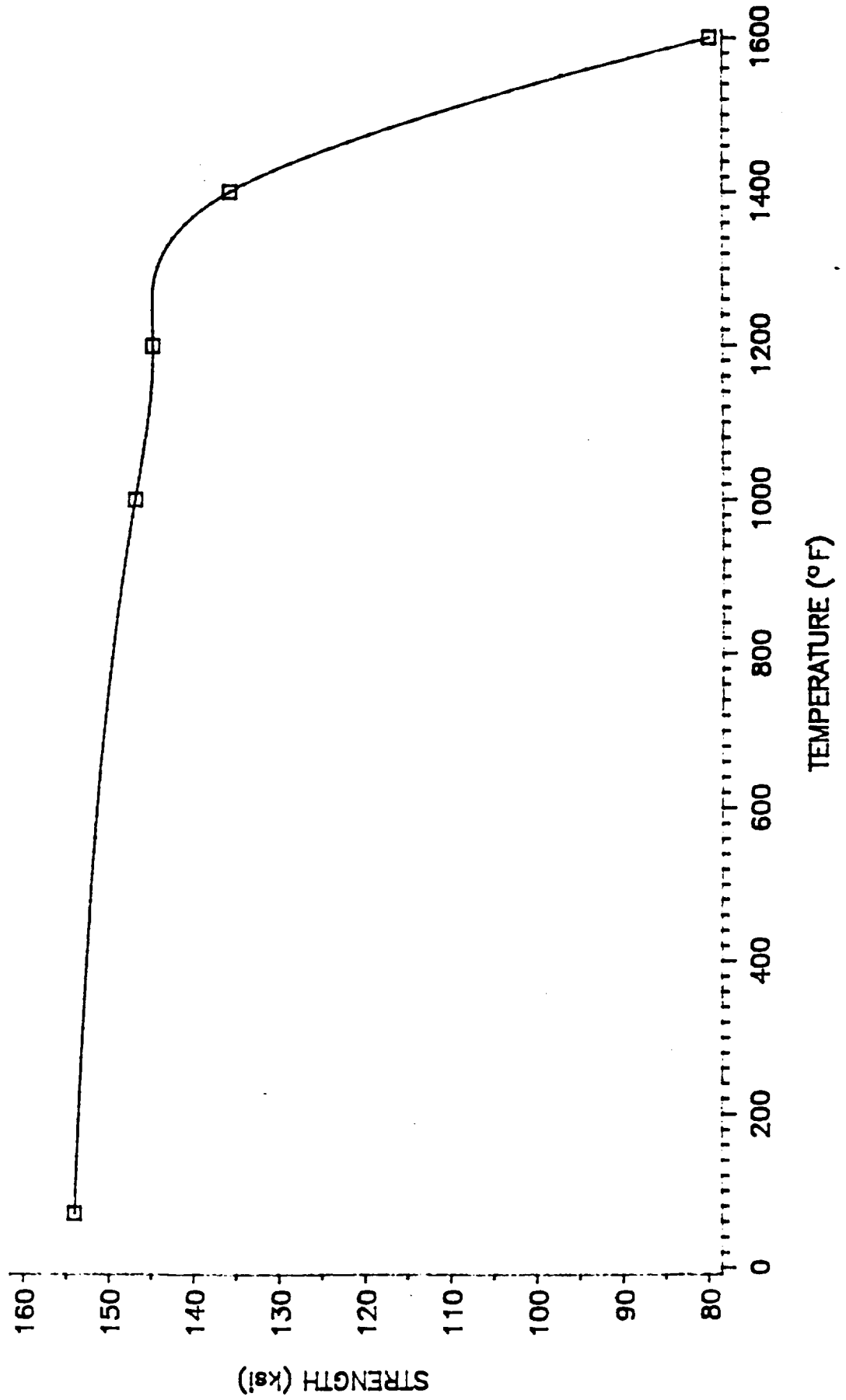
HEAT-TREATED BAR
WROUGHT ALLOY

EFFECT OF TEMPERATURE ON TENSILE STRENGTH FOR RENE 41



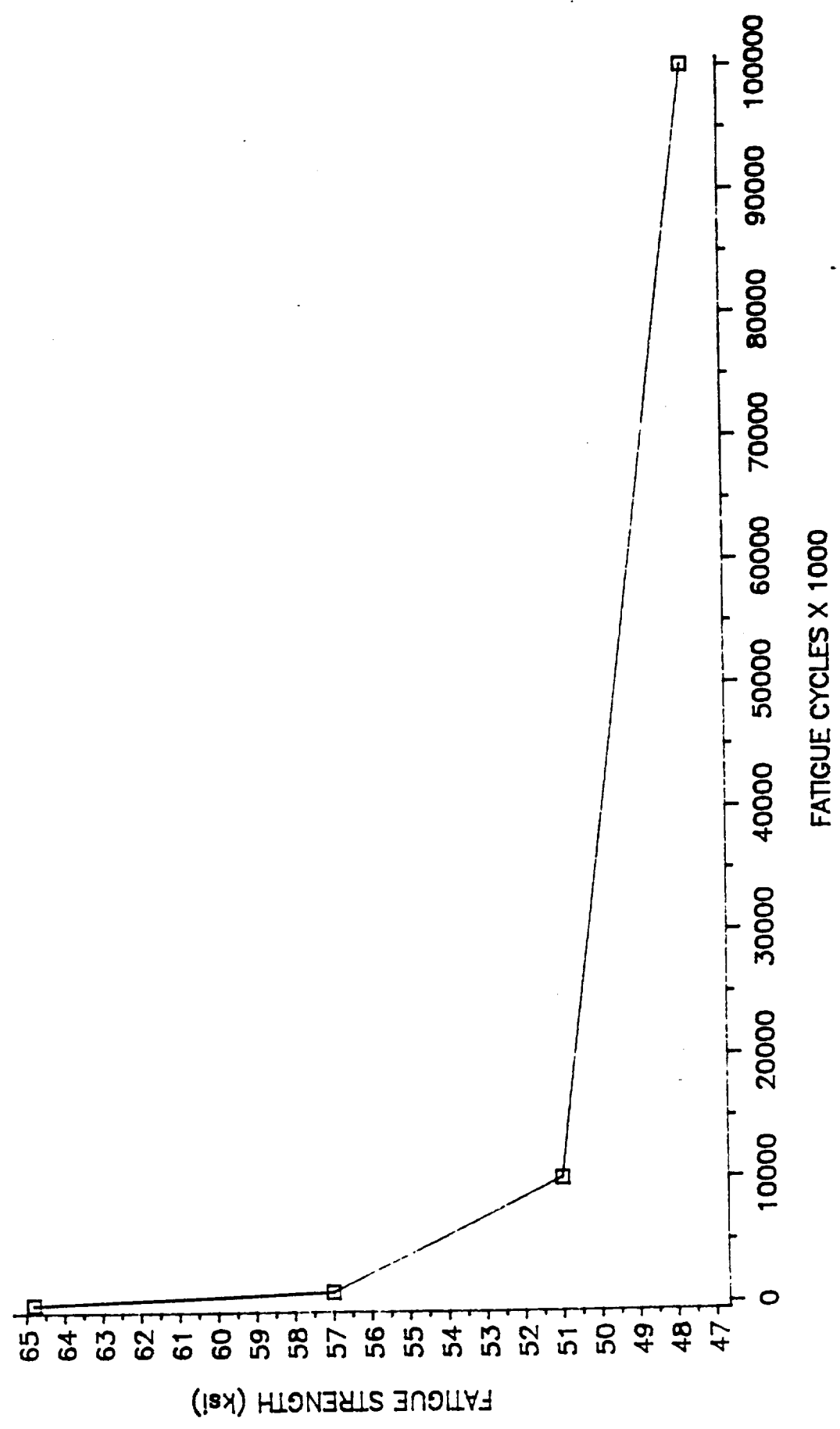
HEAT-TREATED BAR
WROUGHT ALLOY

EFFECT OF TEMPERATURE ON YIELD STRENGTH FOR RENE 41

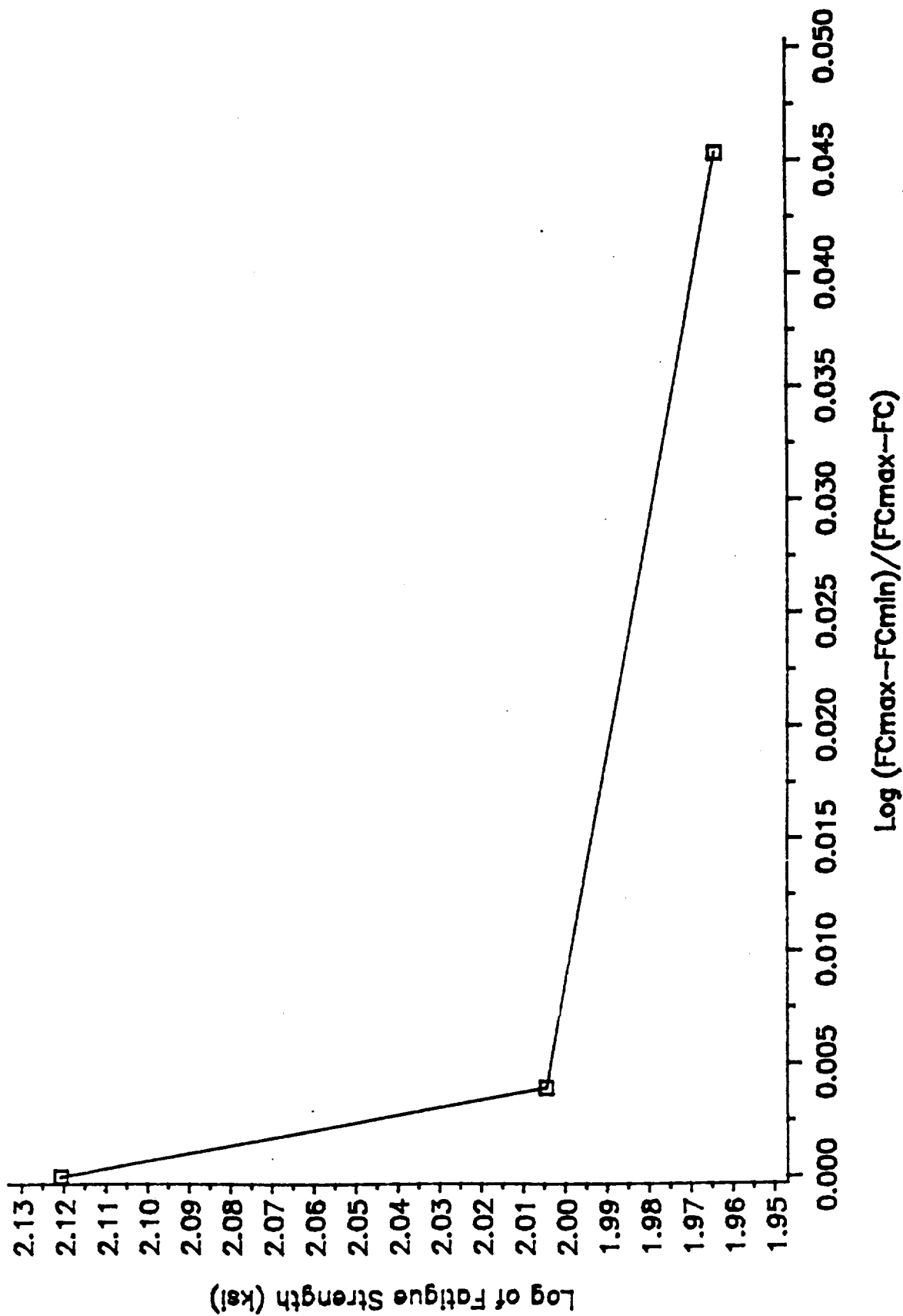


TEST TEMP. - R. T.
SOLUTION-TREATED

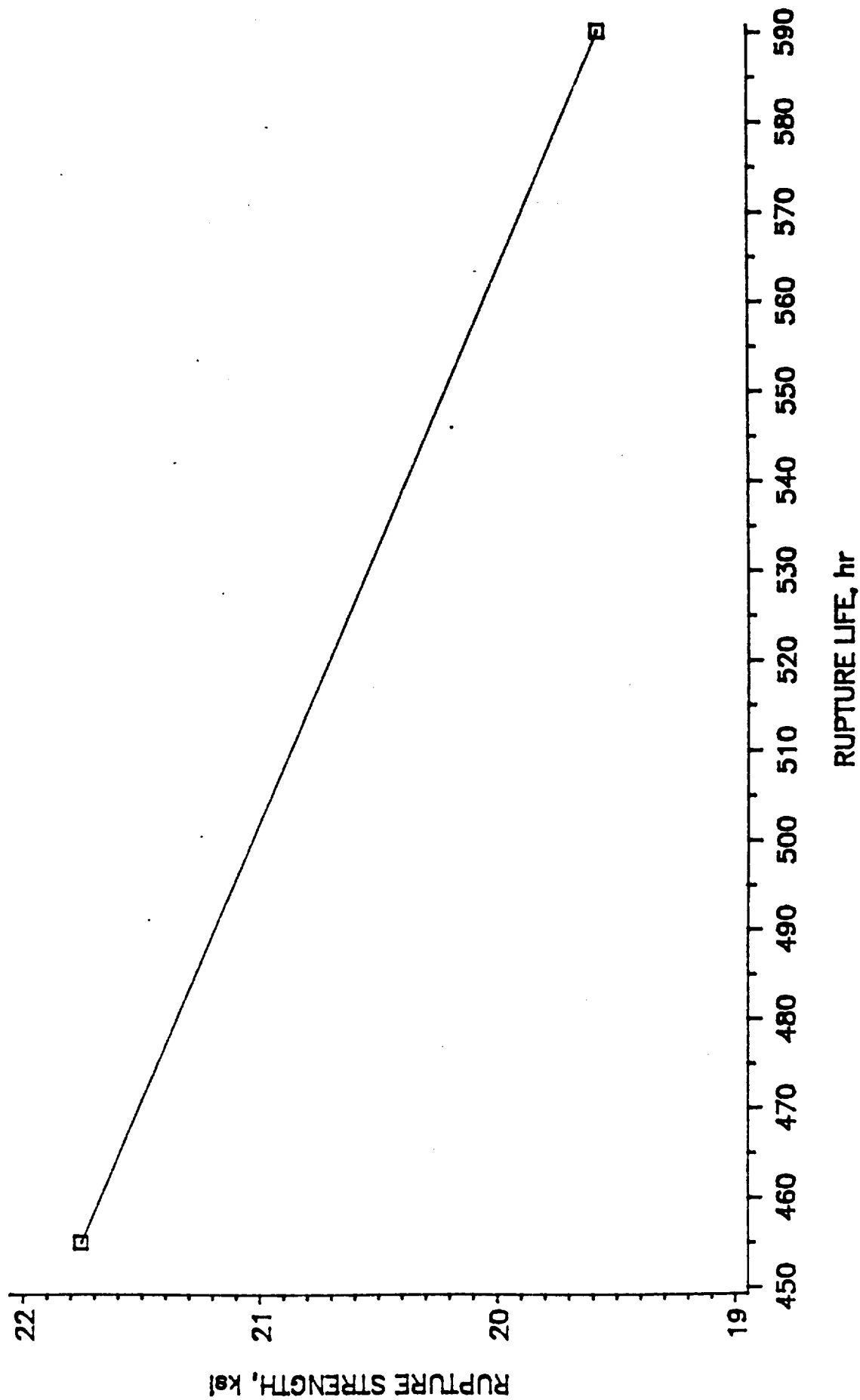
EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 601



EFFECT OF CYCLES ON FATIGUE STRENGTH FOR INCONEL 601

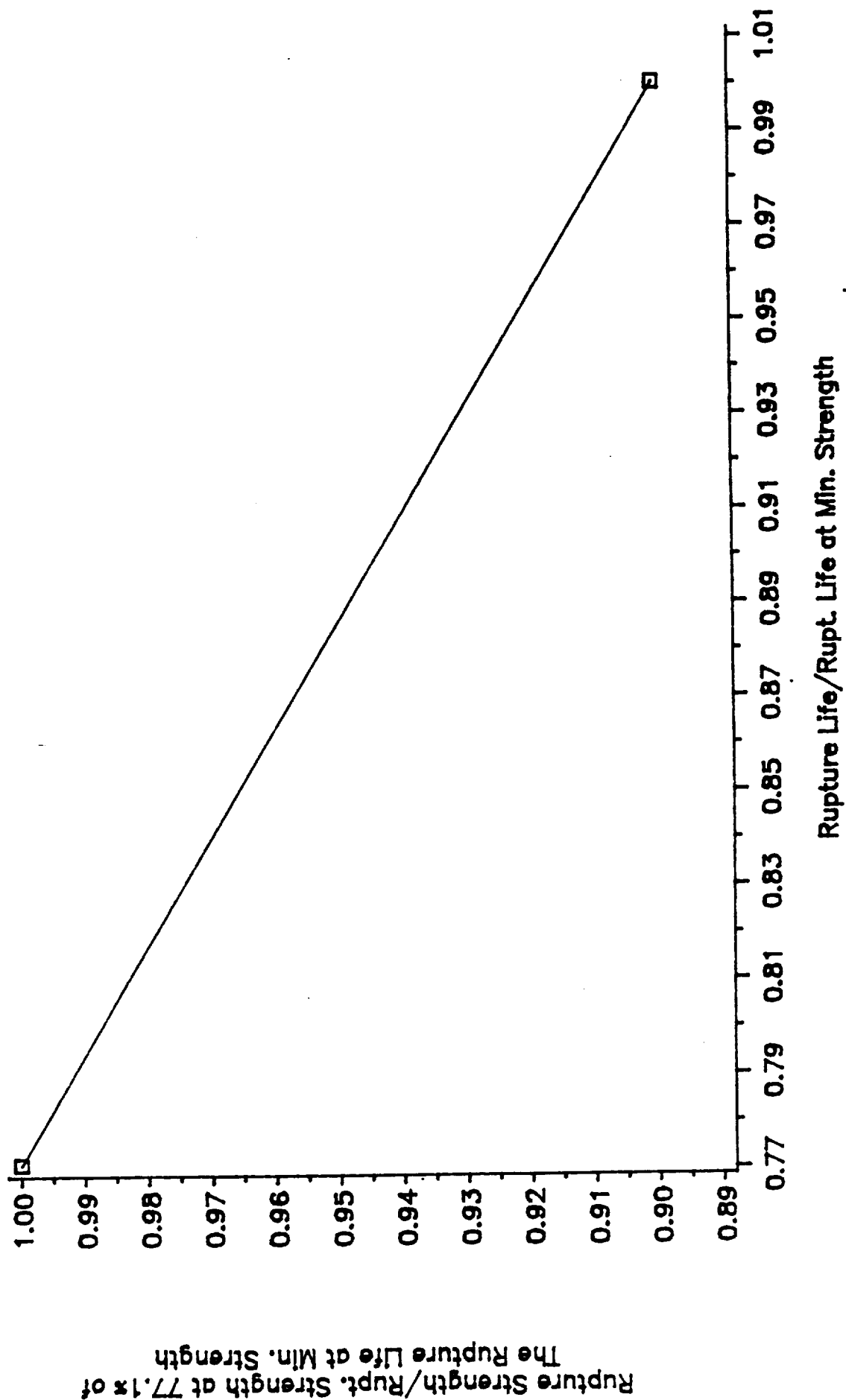


TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH
FOR 218CS TUNGSTEN FIBER/NIOBIUM COMPOSITE

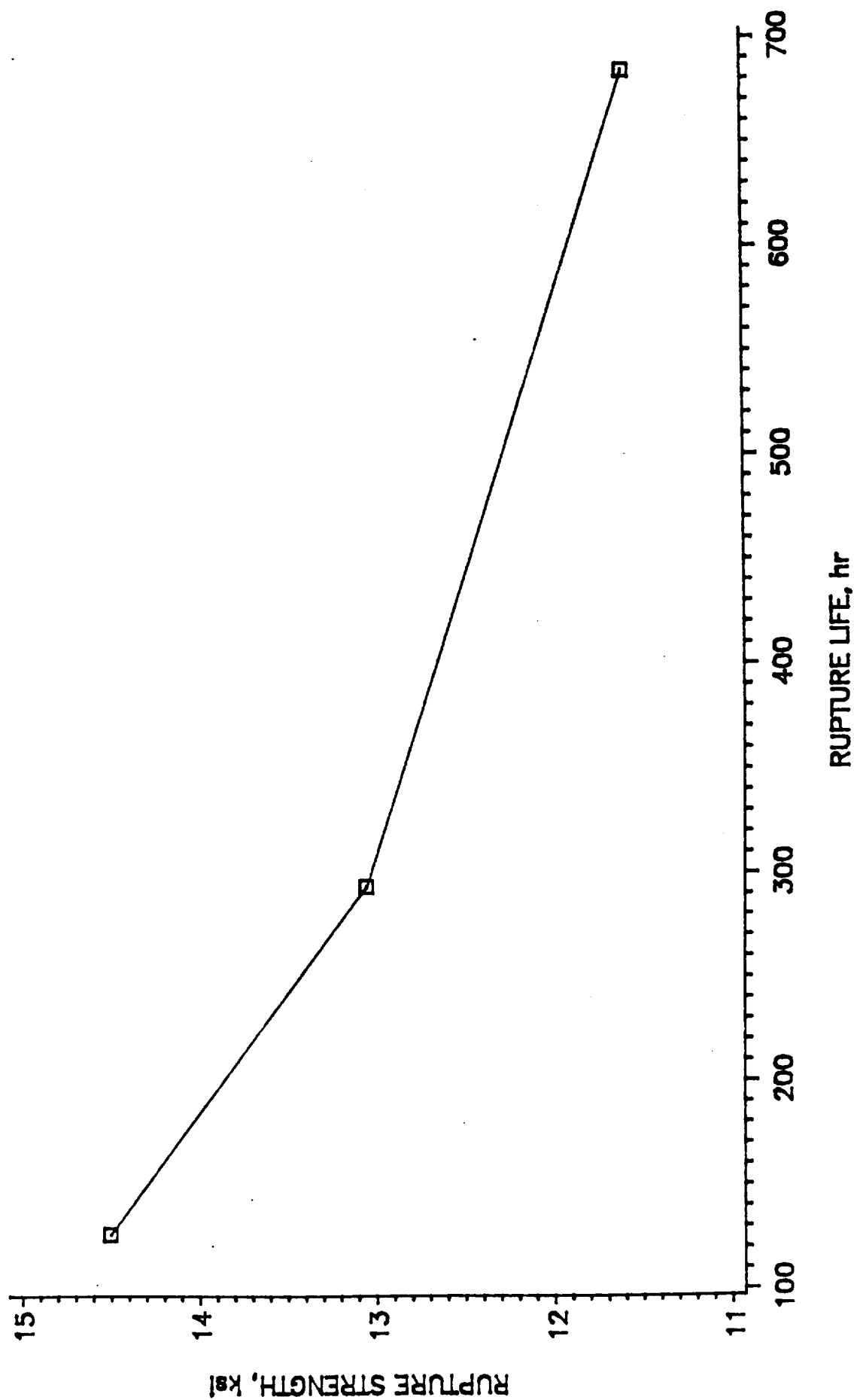
TEST TEMP. = 1400 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR 218CS TUNGSTEN FIBER/NIOBIUM COMPOSITE



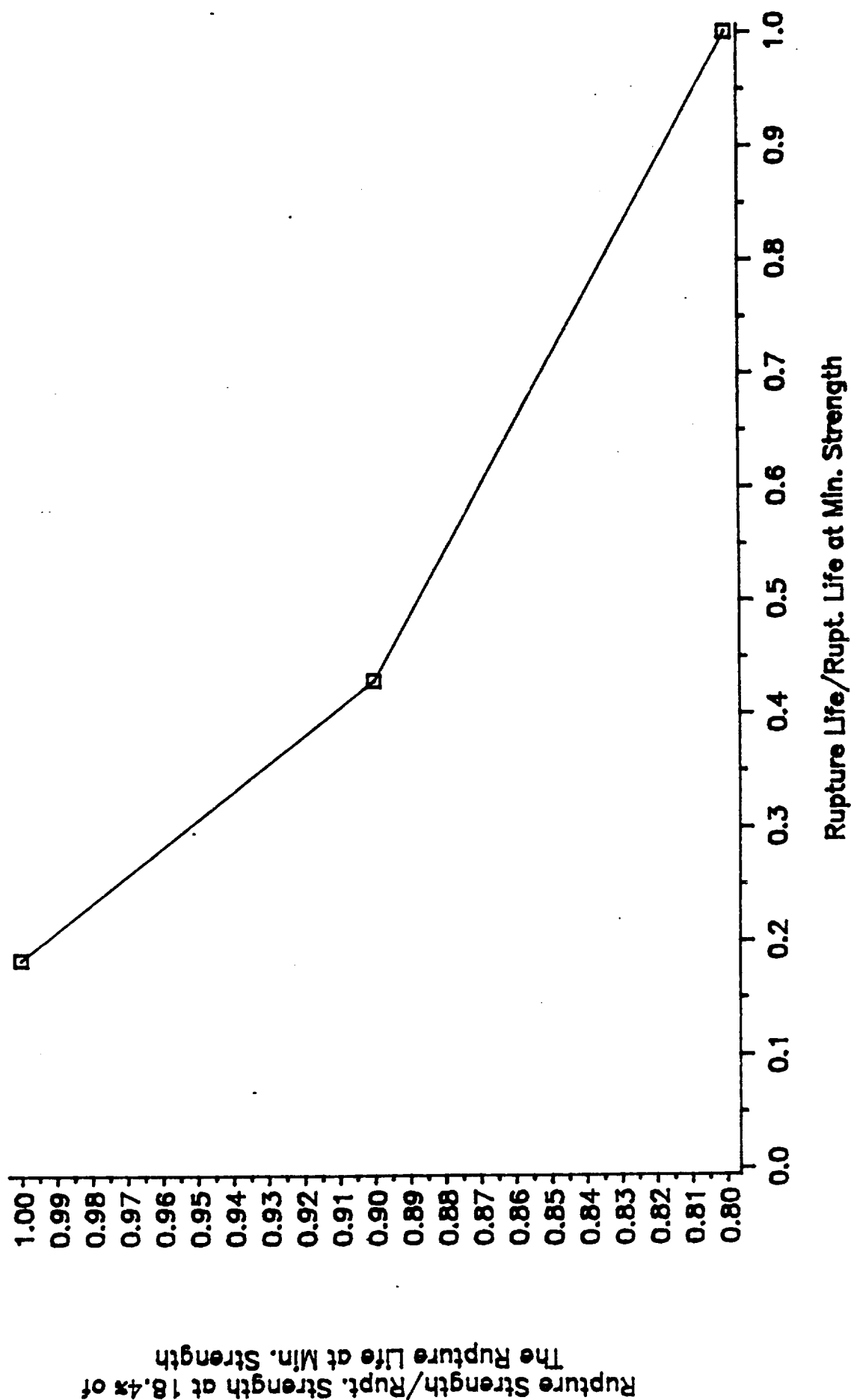
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR 218CS TUNGSTEN FIBER/NIOBIUM COMPOSITE



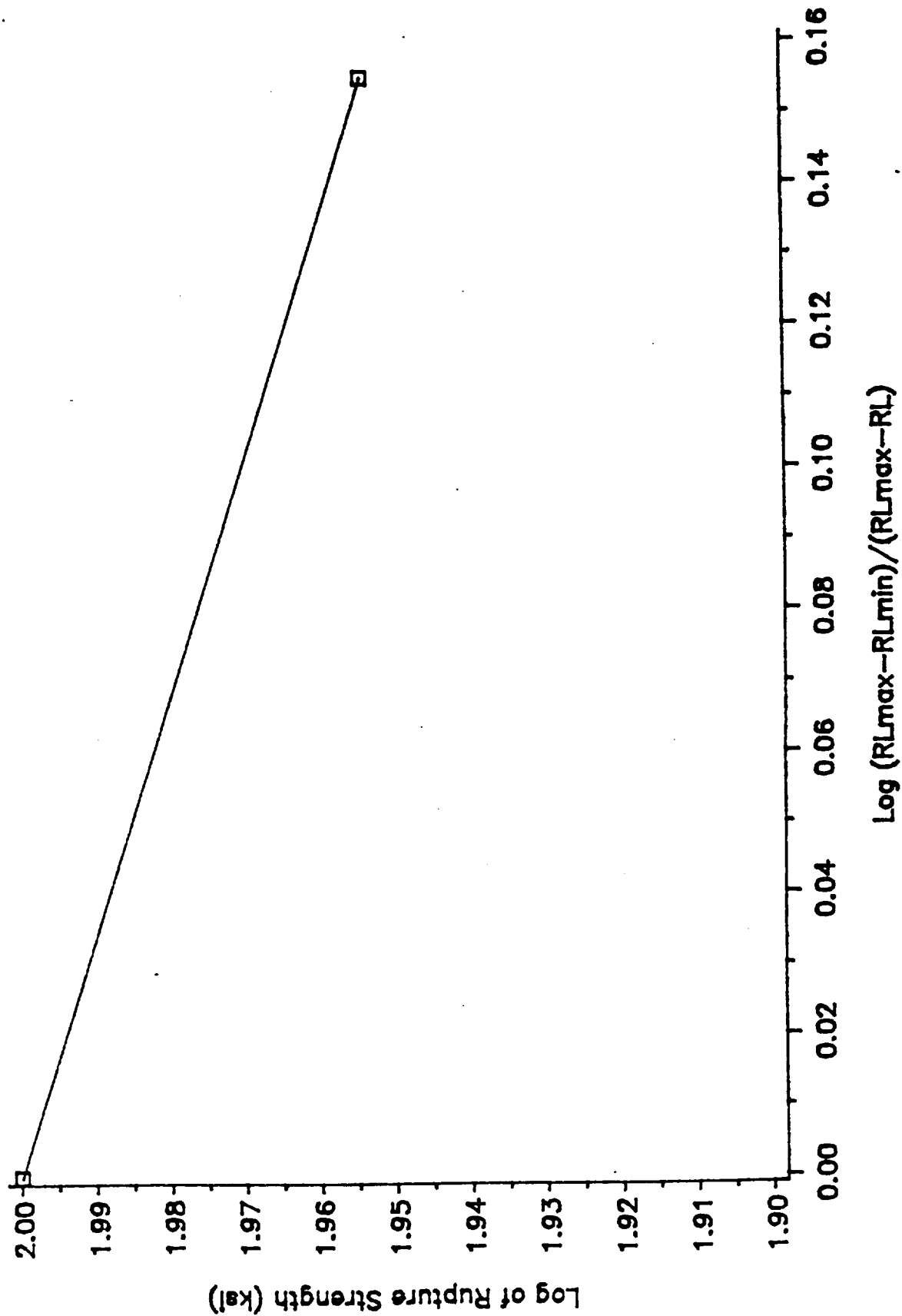
TEST TEMP. = 1500 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR 218CS TUNGSTEN FIBER/NIOBIUM COMPOSITE



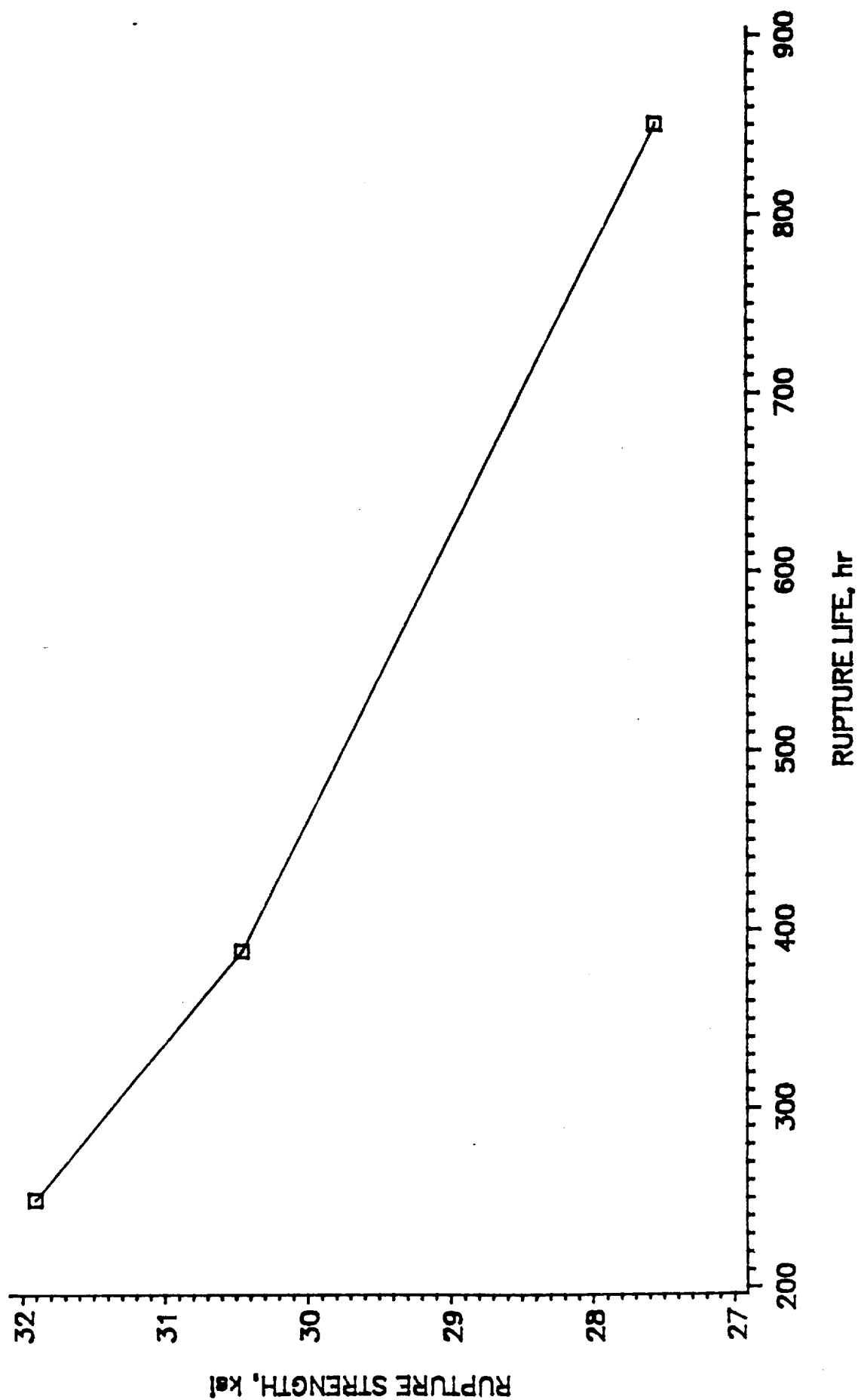
TEST TEMP. -- 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH
FOR 218CS TUNGSTEN FIBER/NIOBIUM COMPOSITE



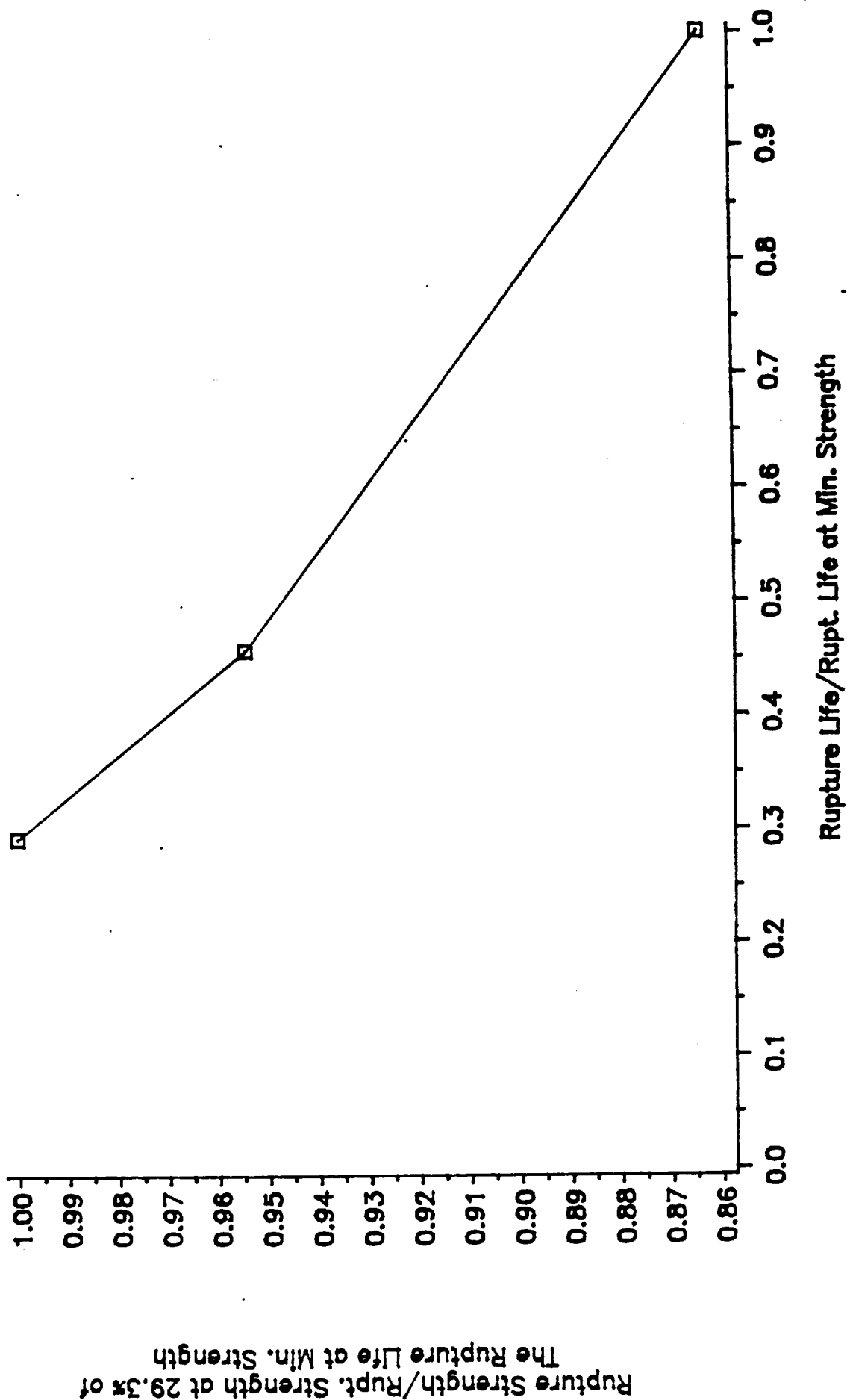
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



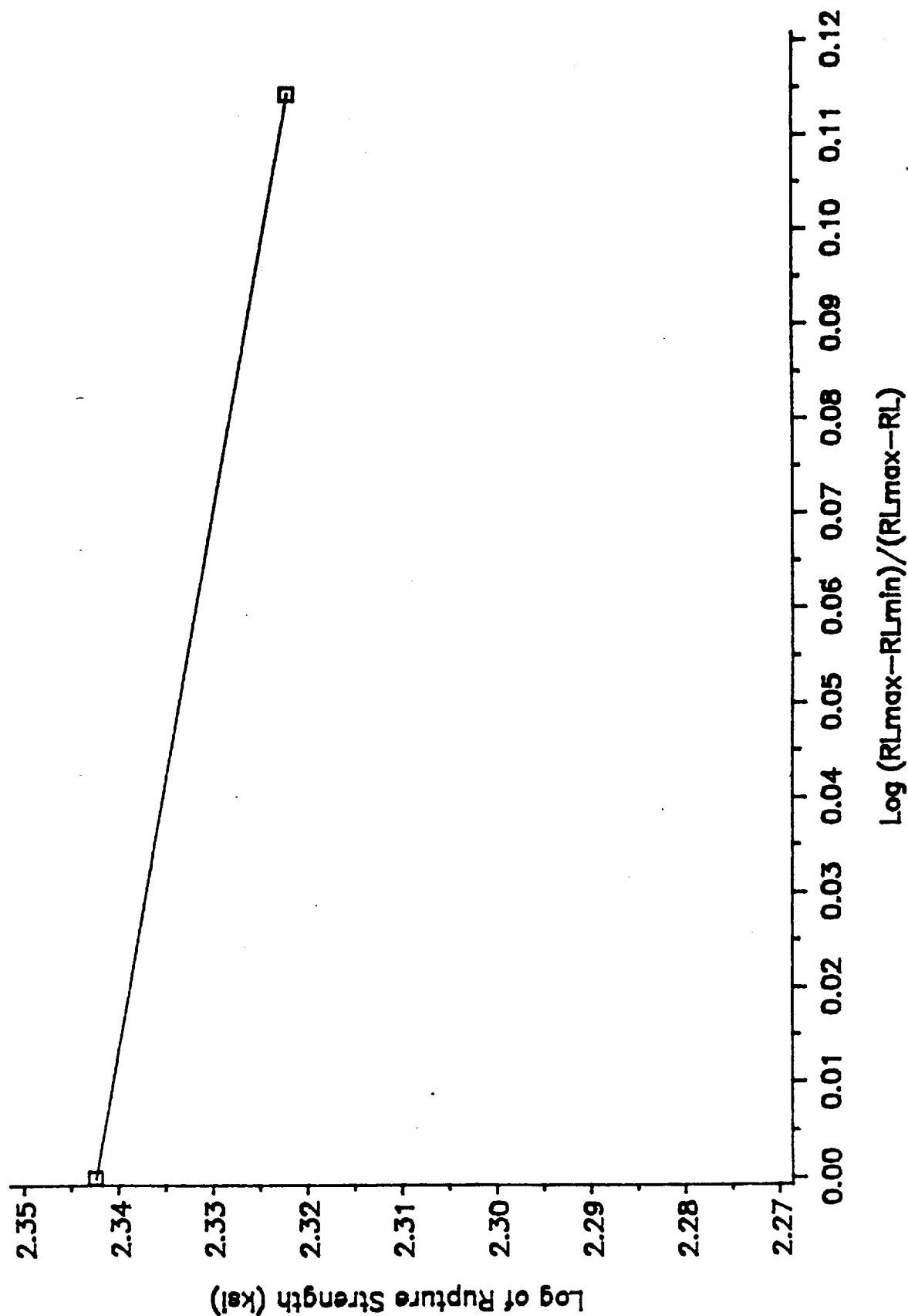
TEST TEMP. = 1400 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



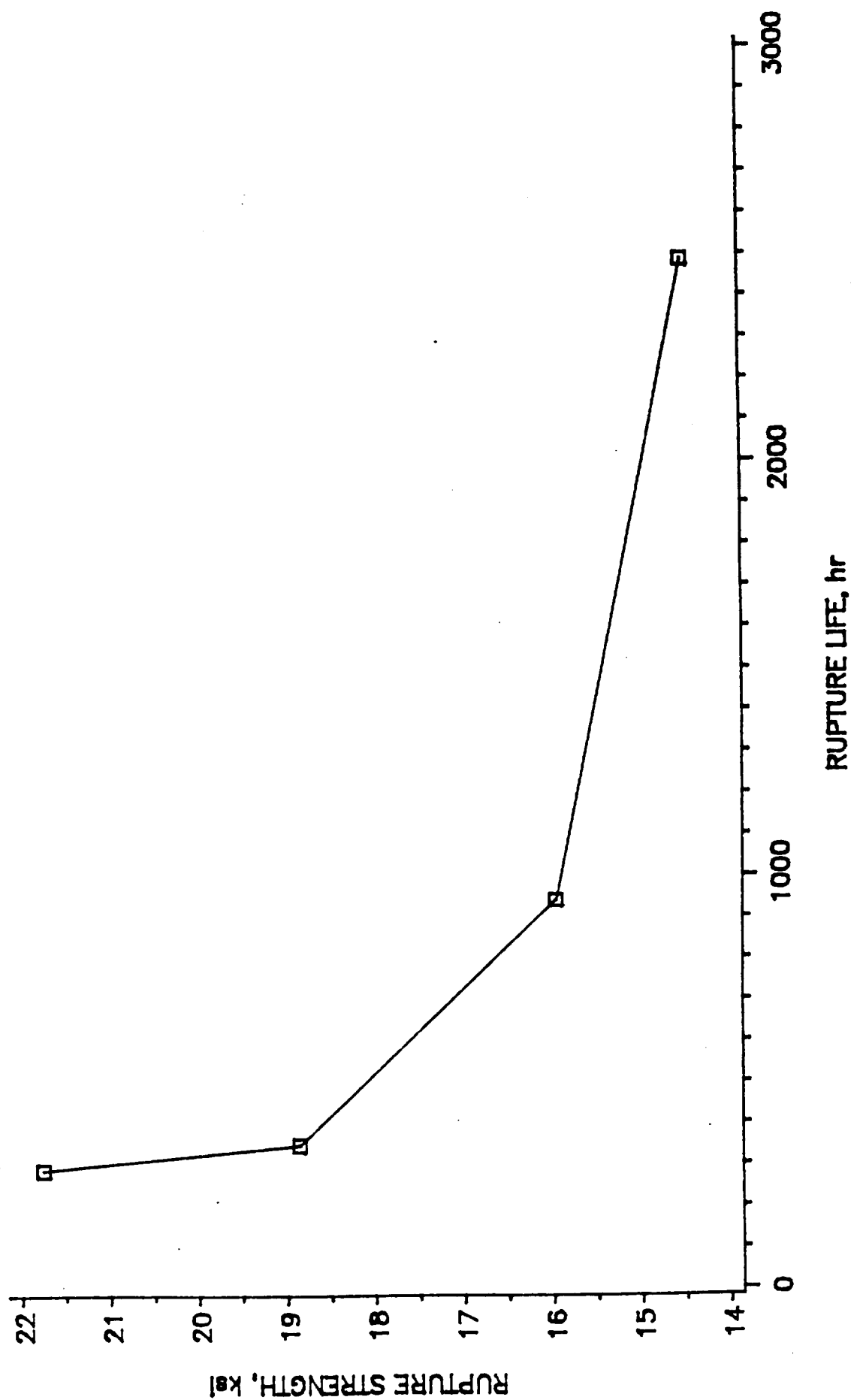
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH
FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



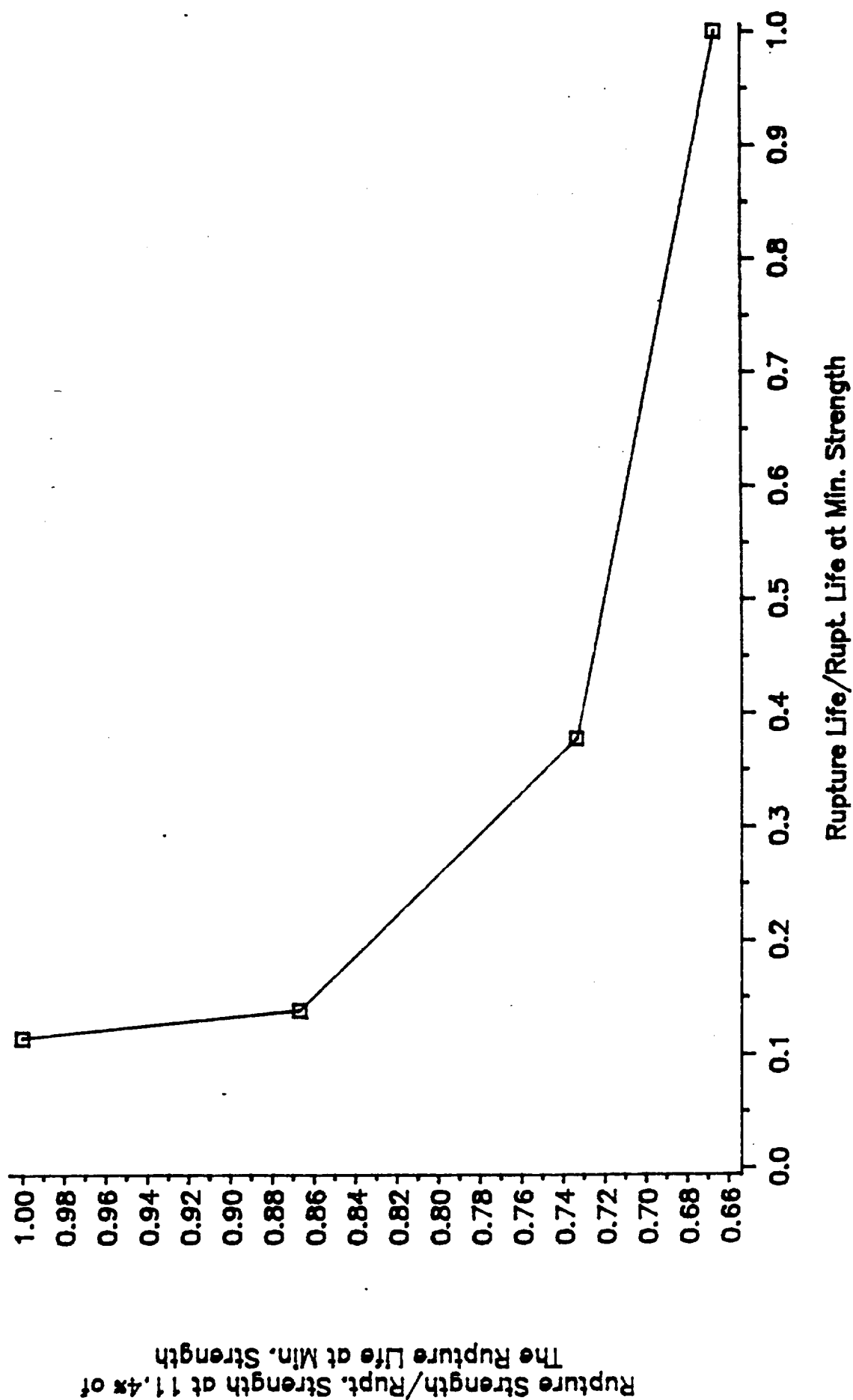
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



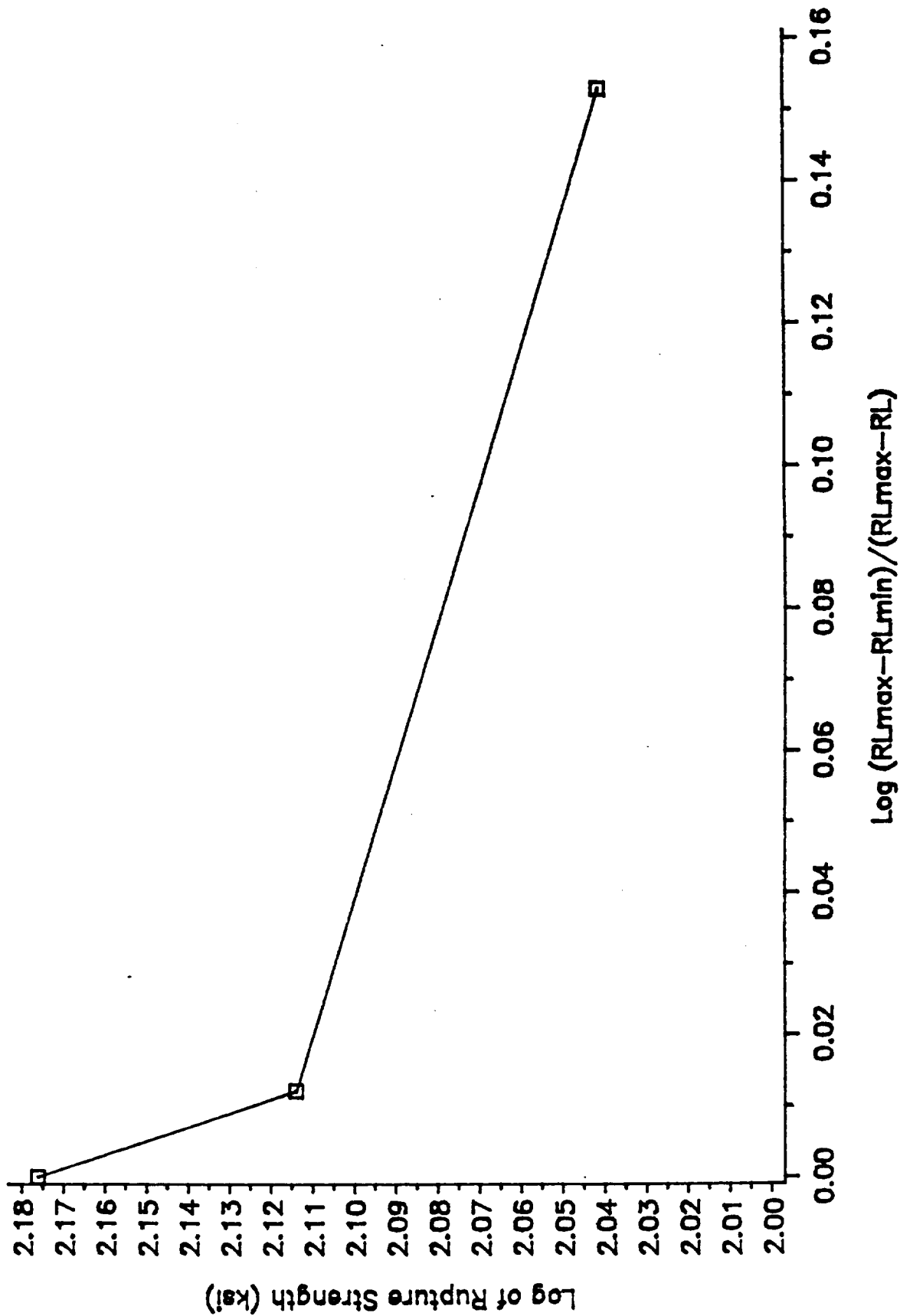
TEST TEMP. = 1500 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



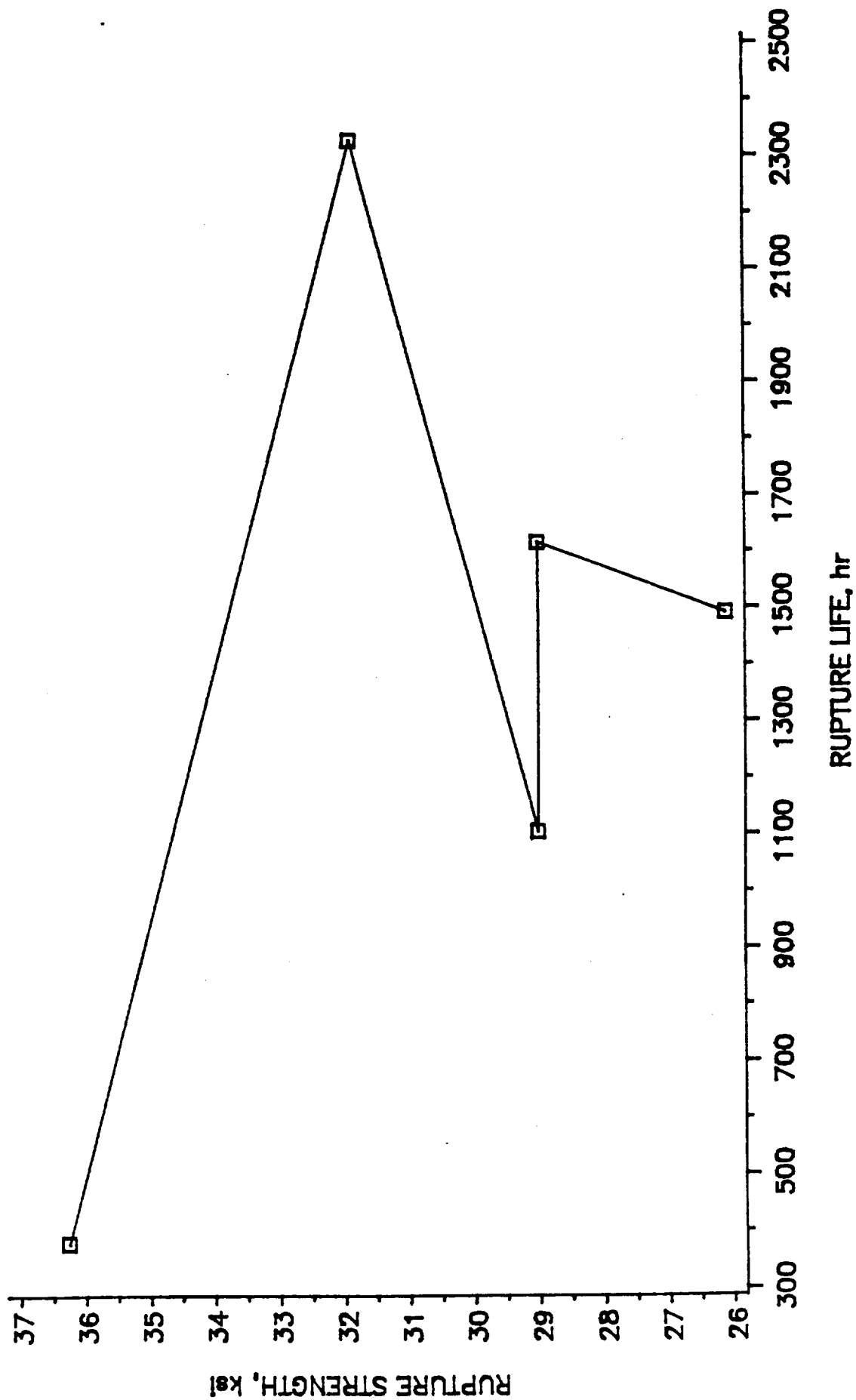
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM COMPOSITE



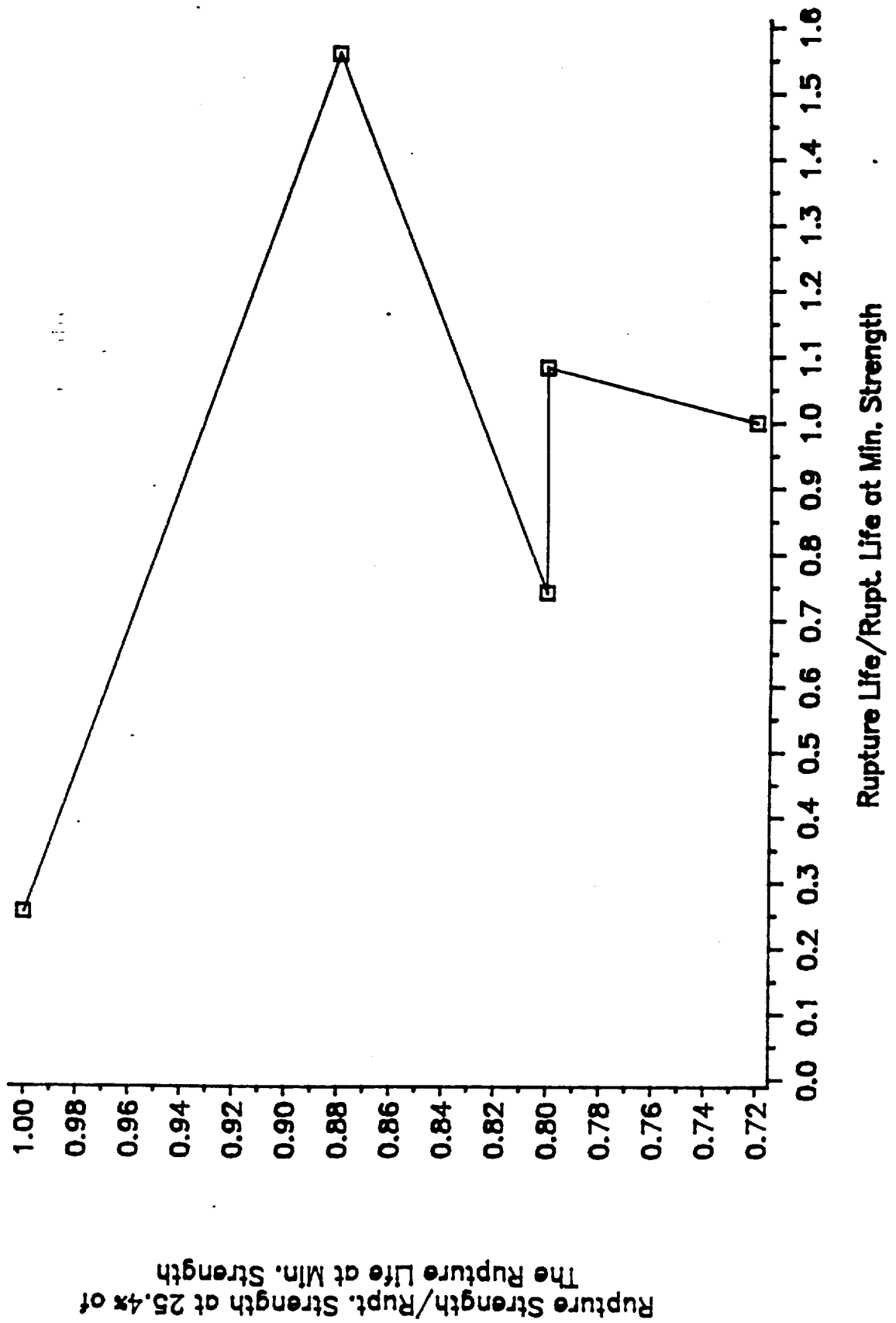
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE



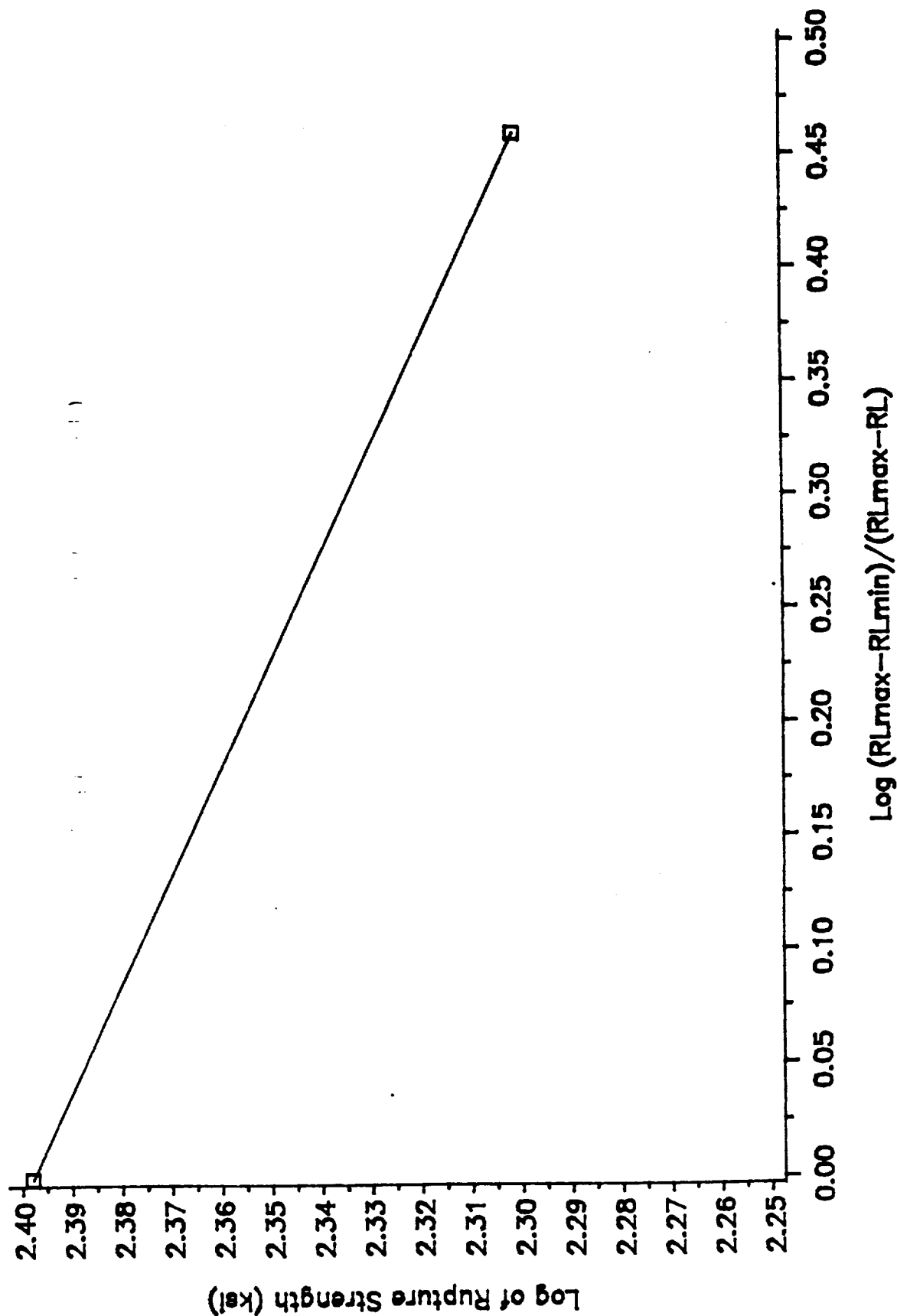
TEST TEMP. = 1400 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE



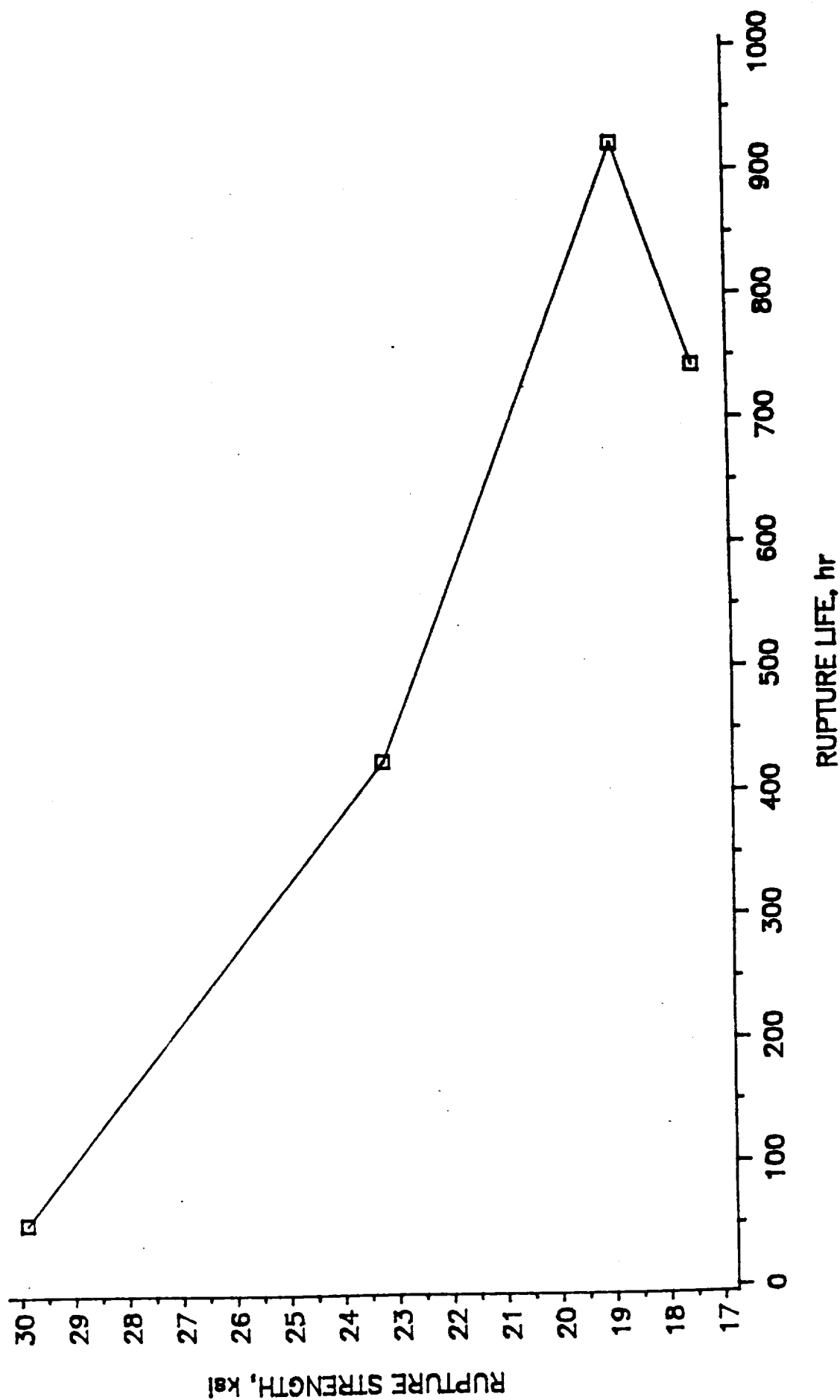
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR
ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE



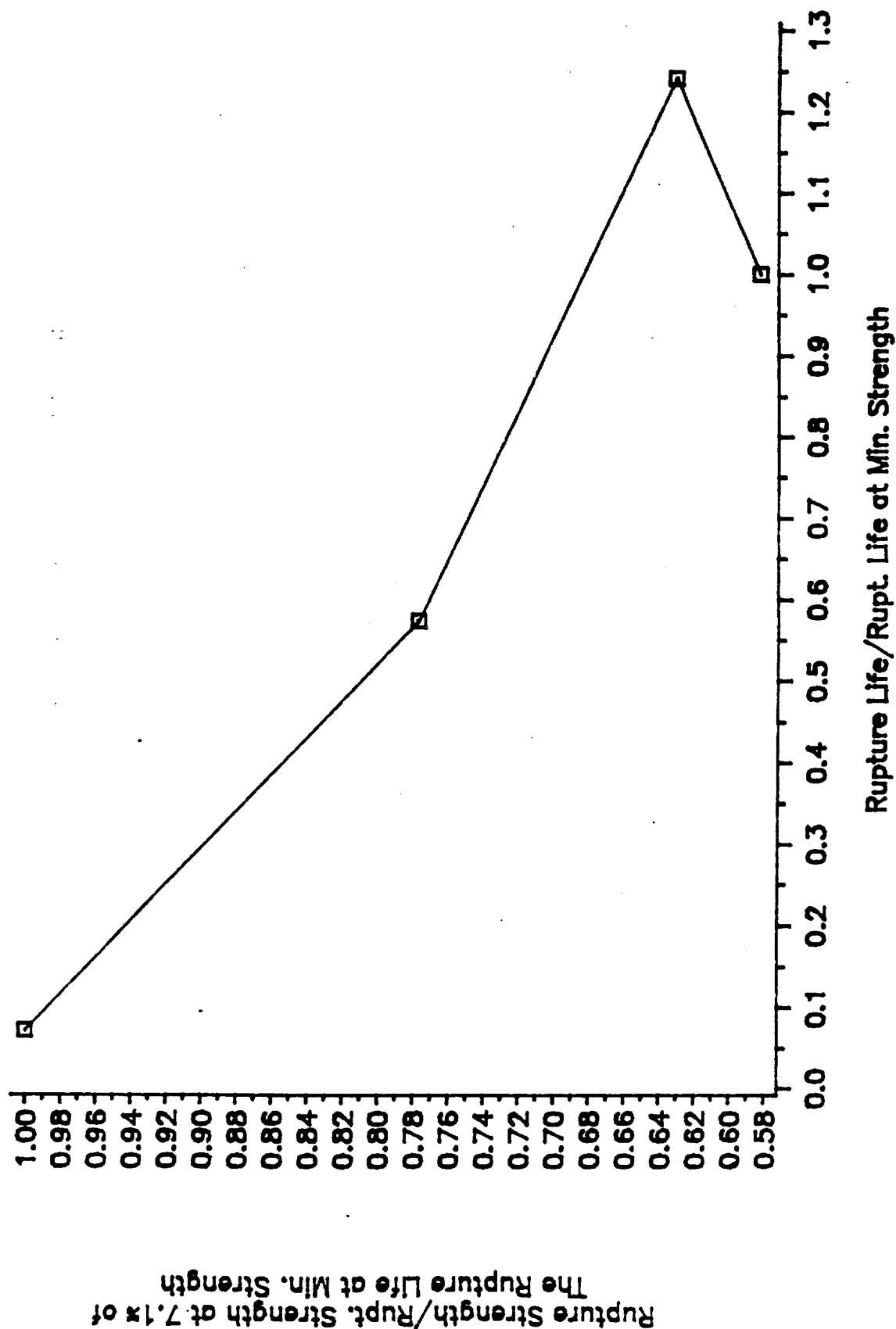
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE



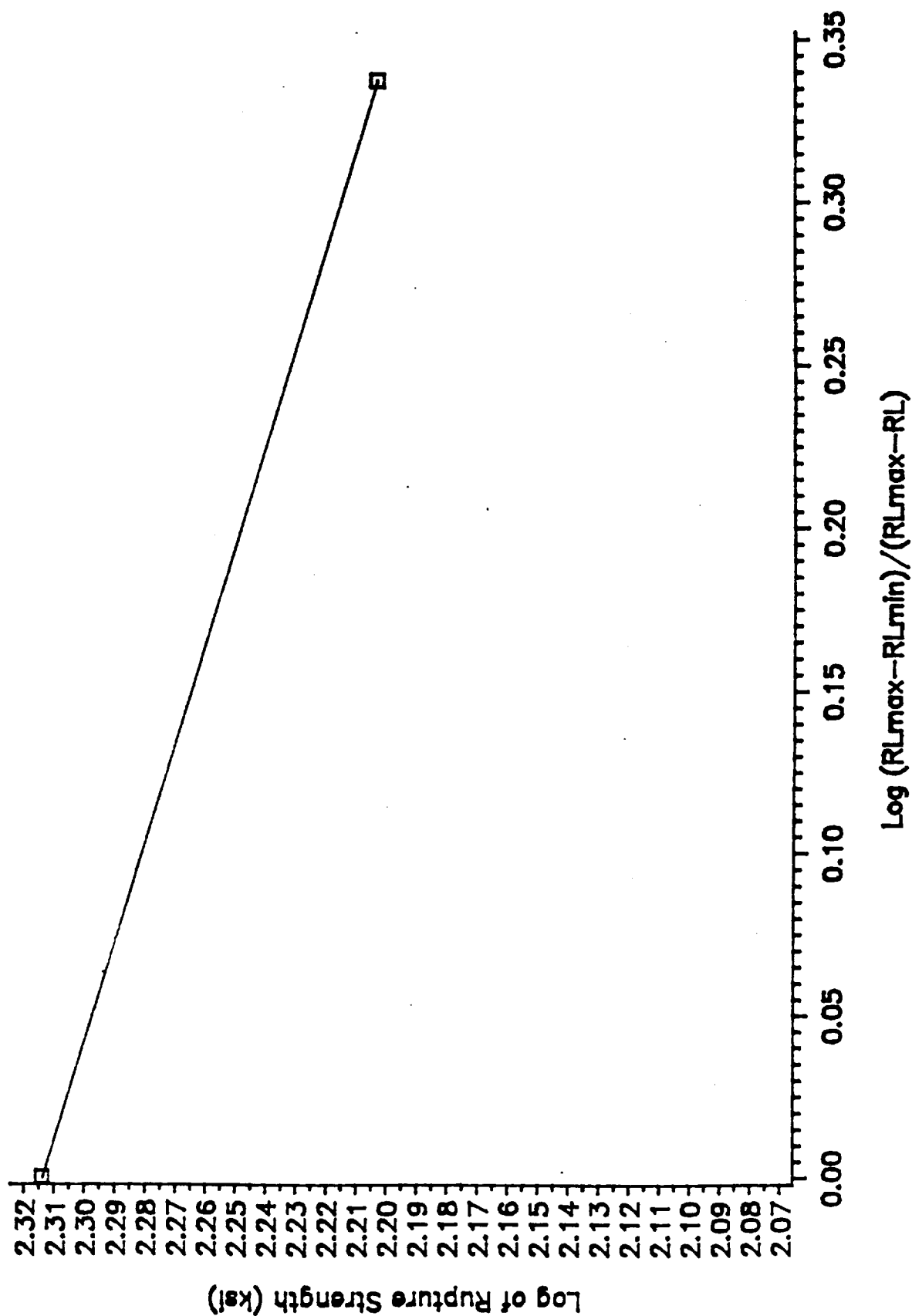
TEST TEMP. = 1500 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE



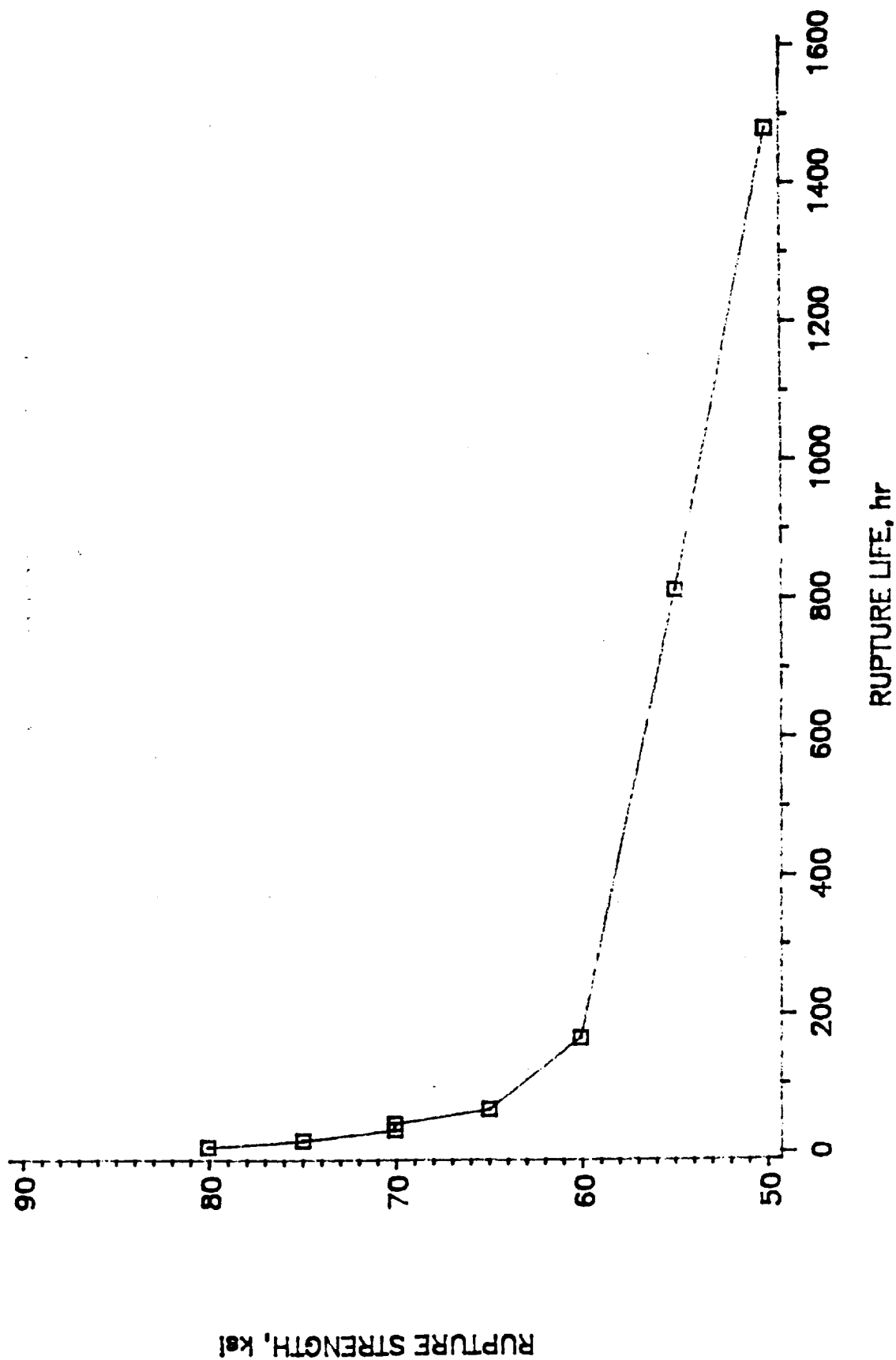
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR ST300 TUNGSTEN FIBER/NIOBIUM-1% ZIRCONIUM COMPOSITE

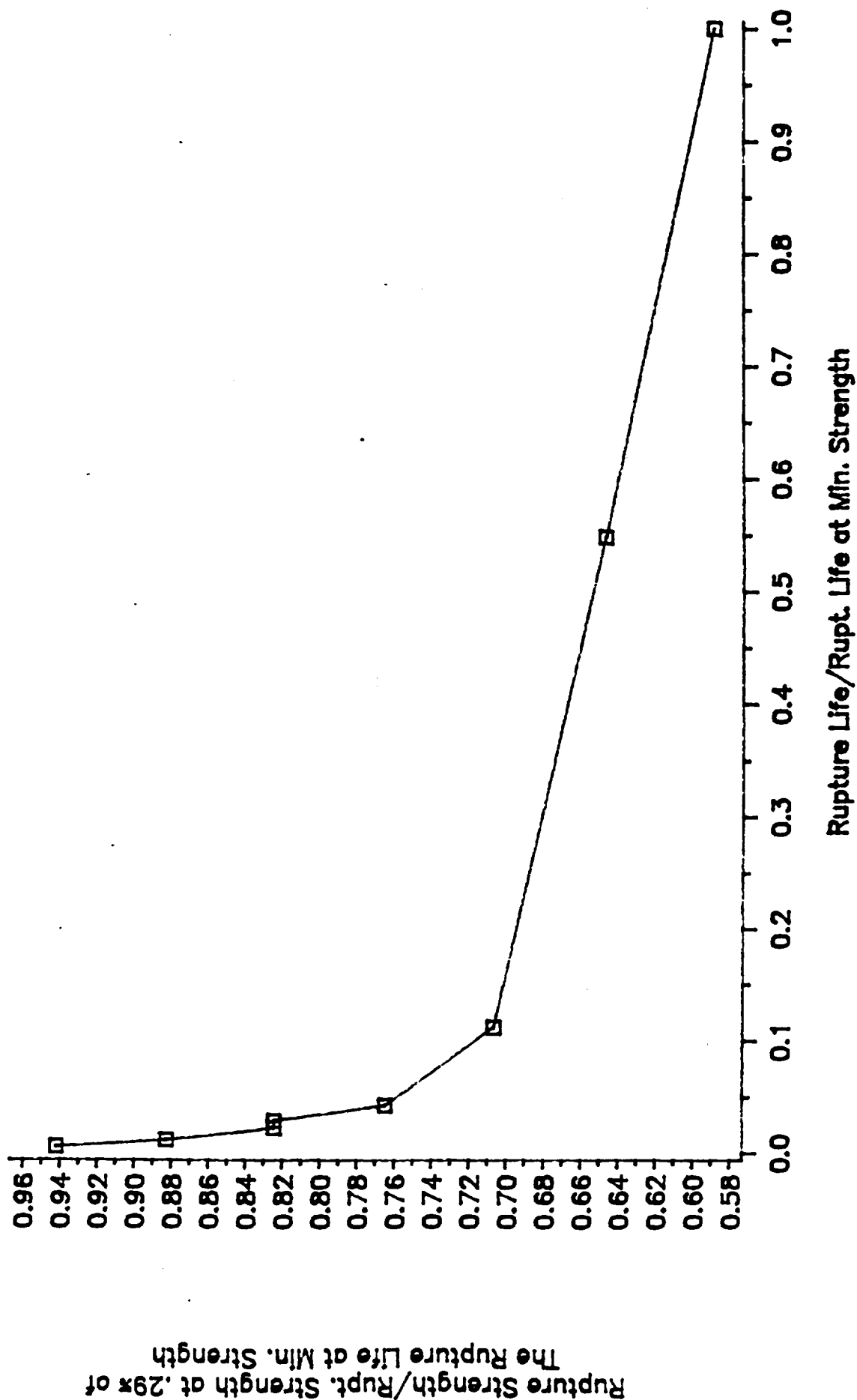


TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TUNGSTEN FIBER 218CS

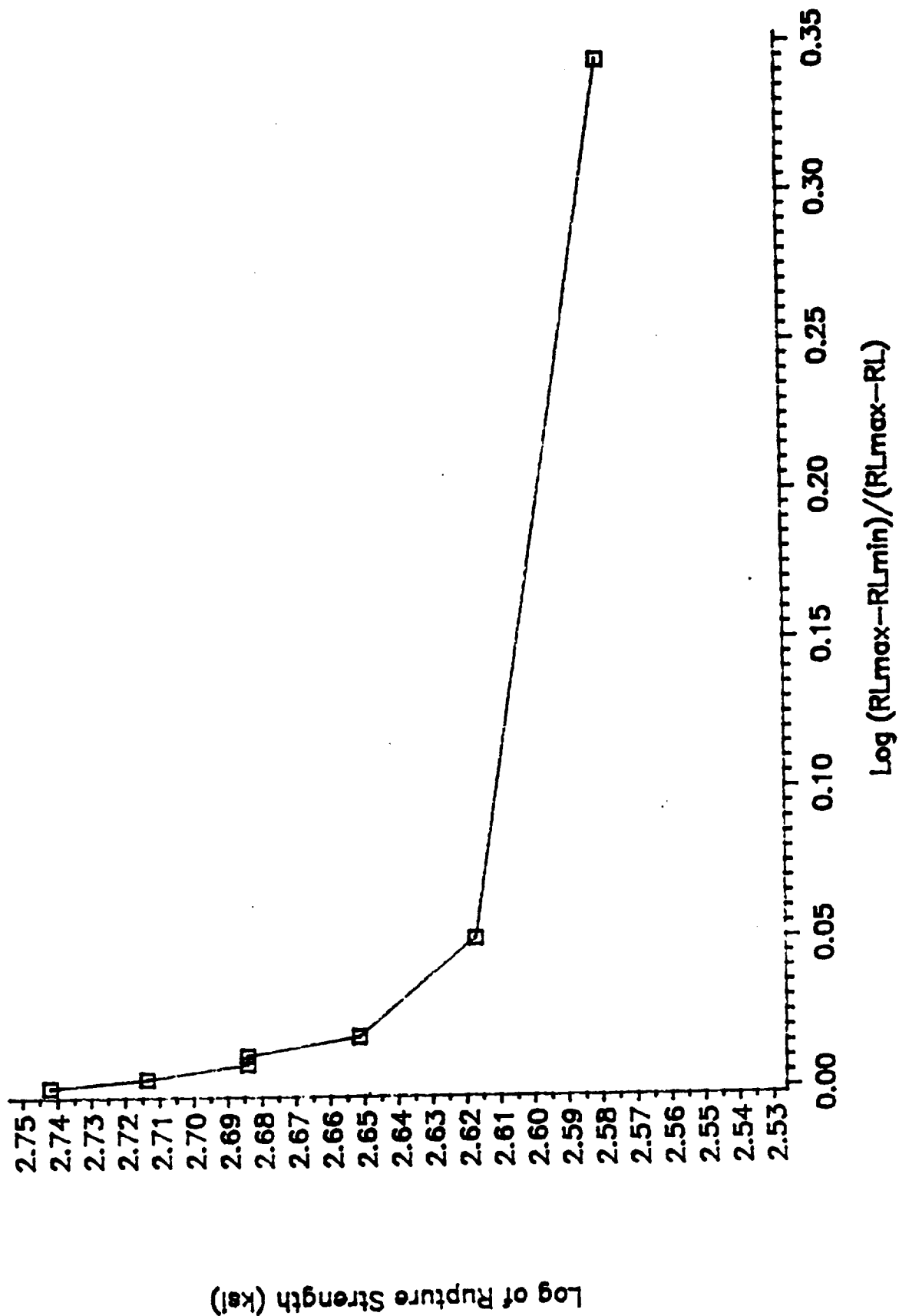


EFFECT OF TIME ON RUPTURE STRENGTH FOR TN218CS



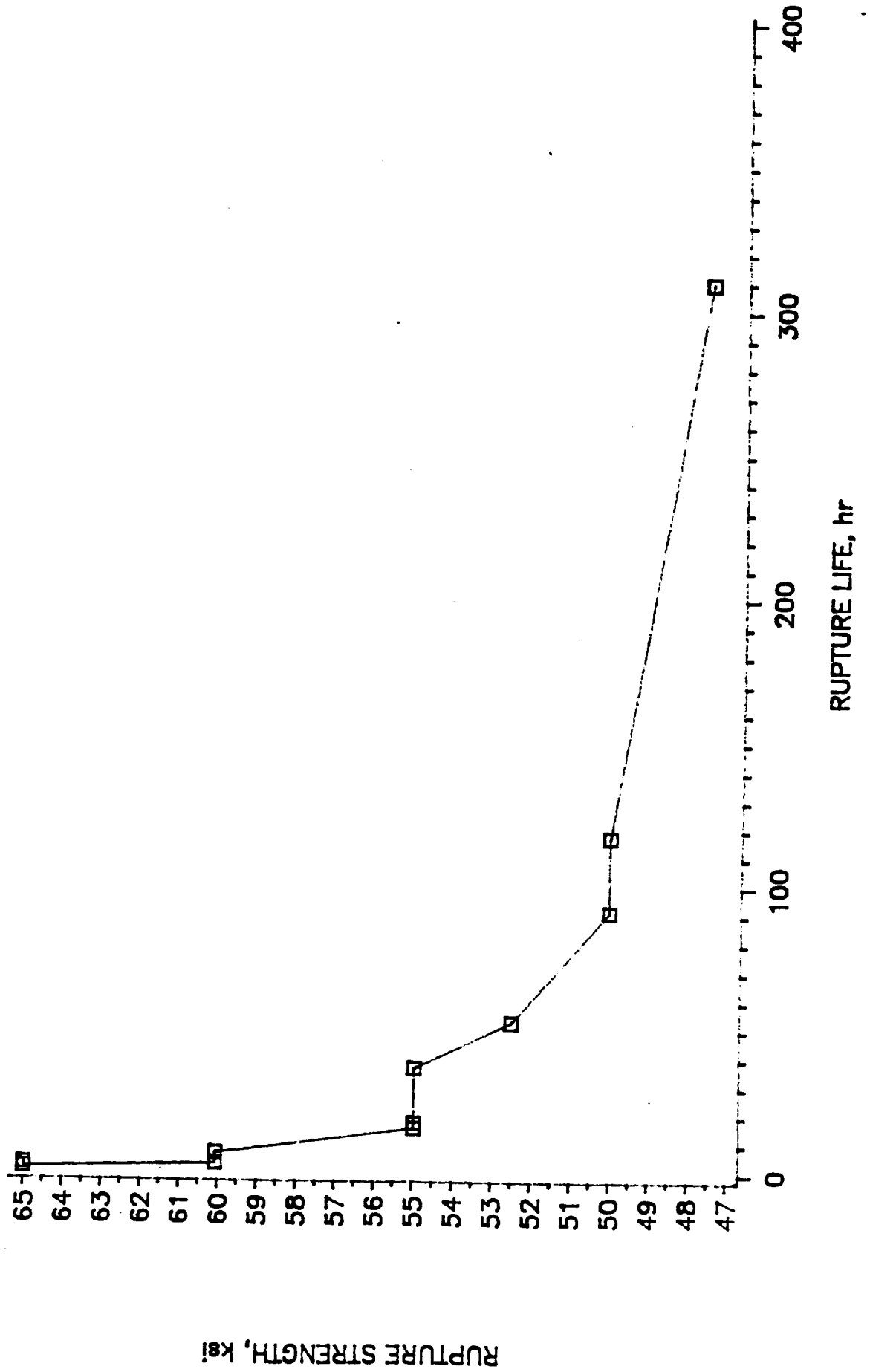
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TN218CS



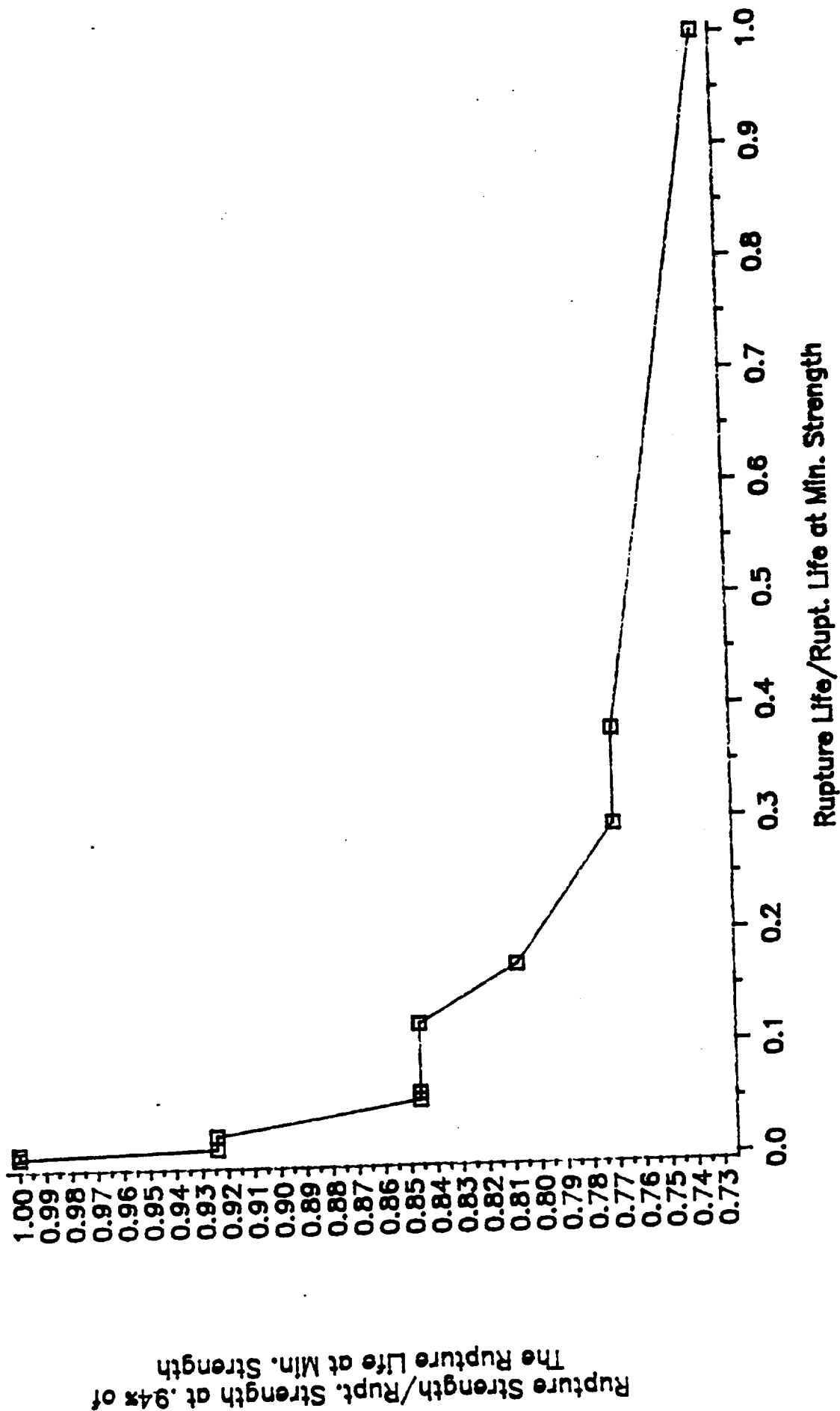
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TUNGSTEN FIBER 218CS



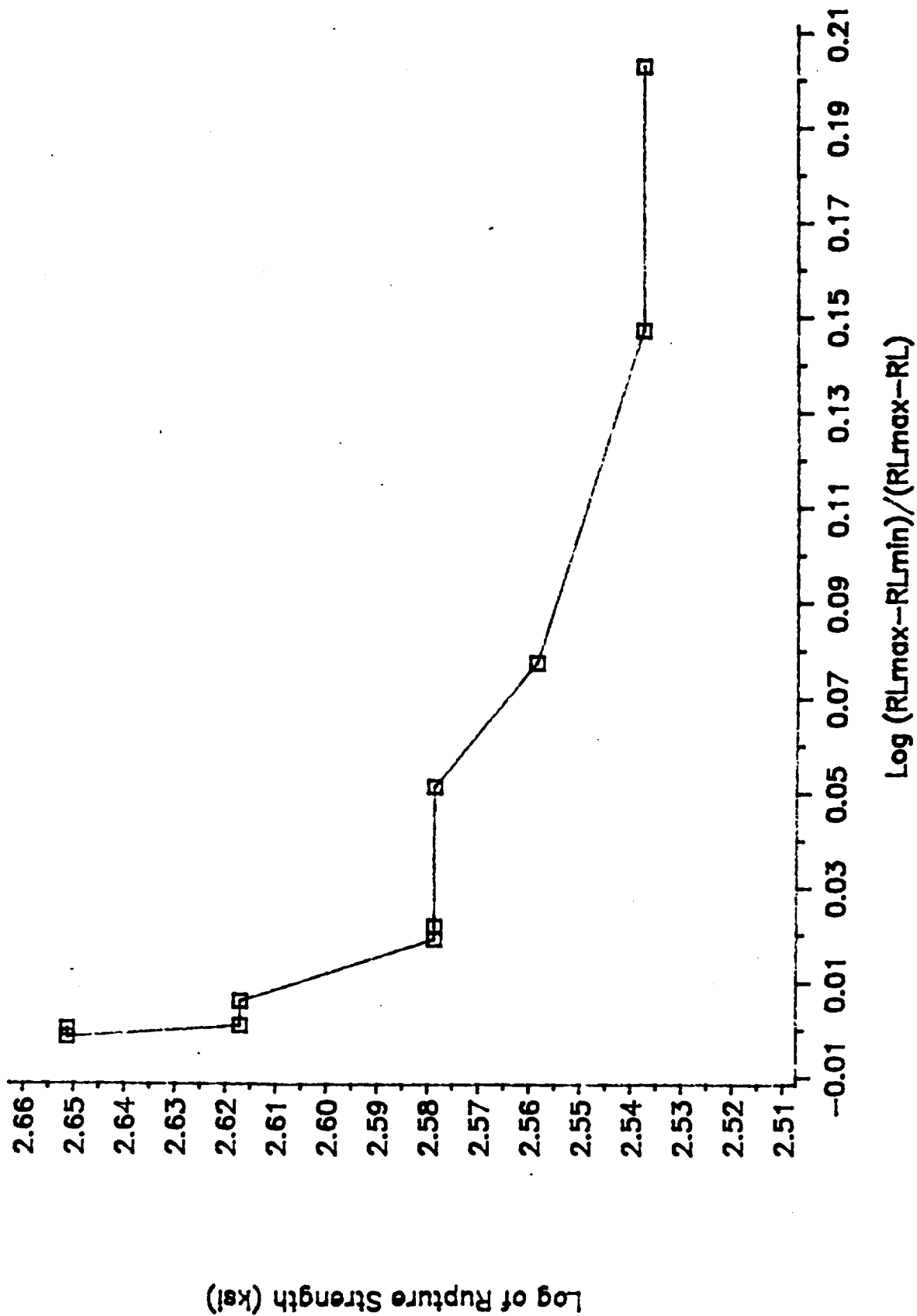
TEST TEMP. = 1500 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR TN218CS



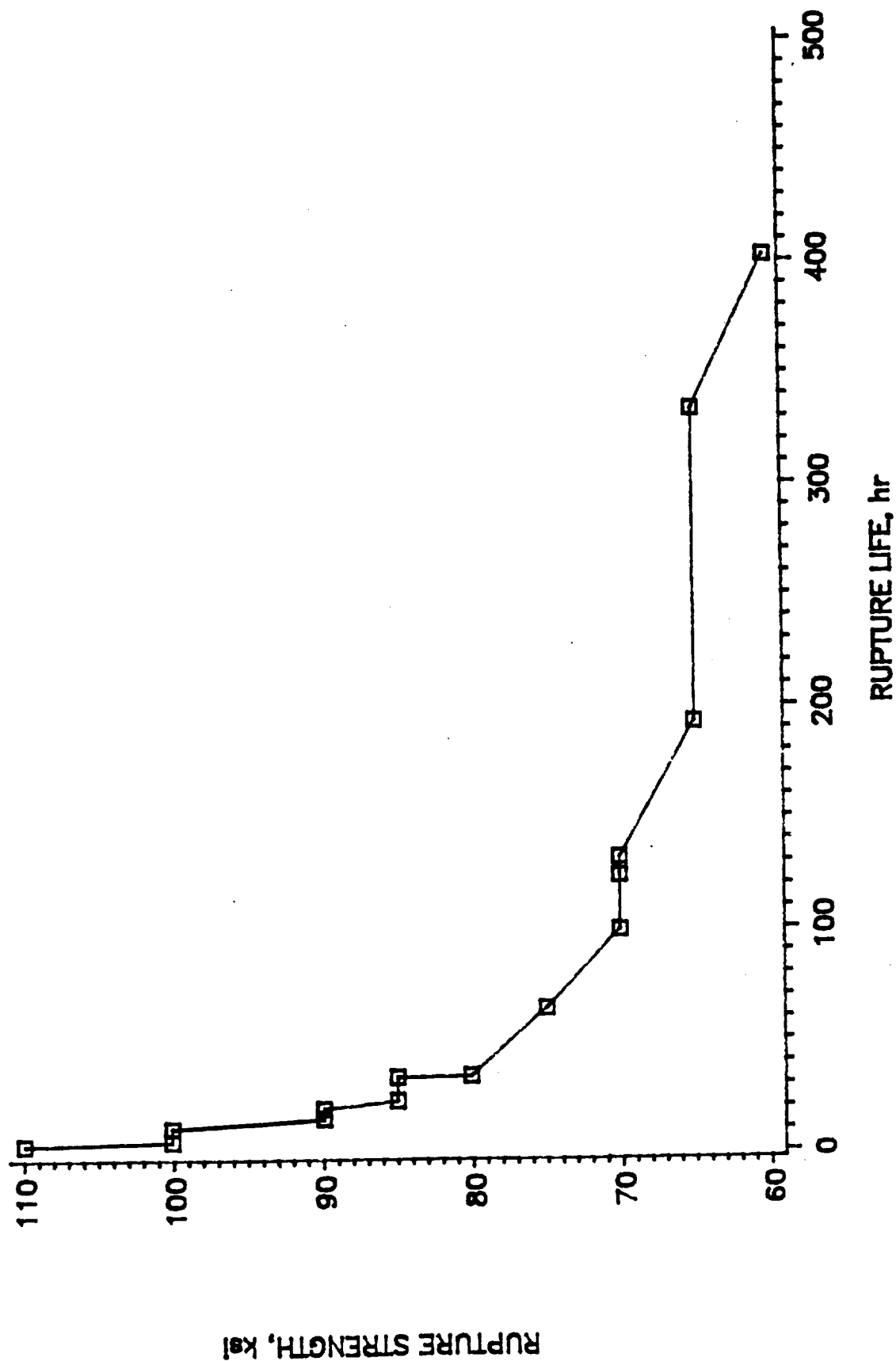
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TN218CS



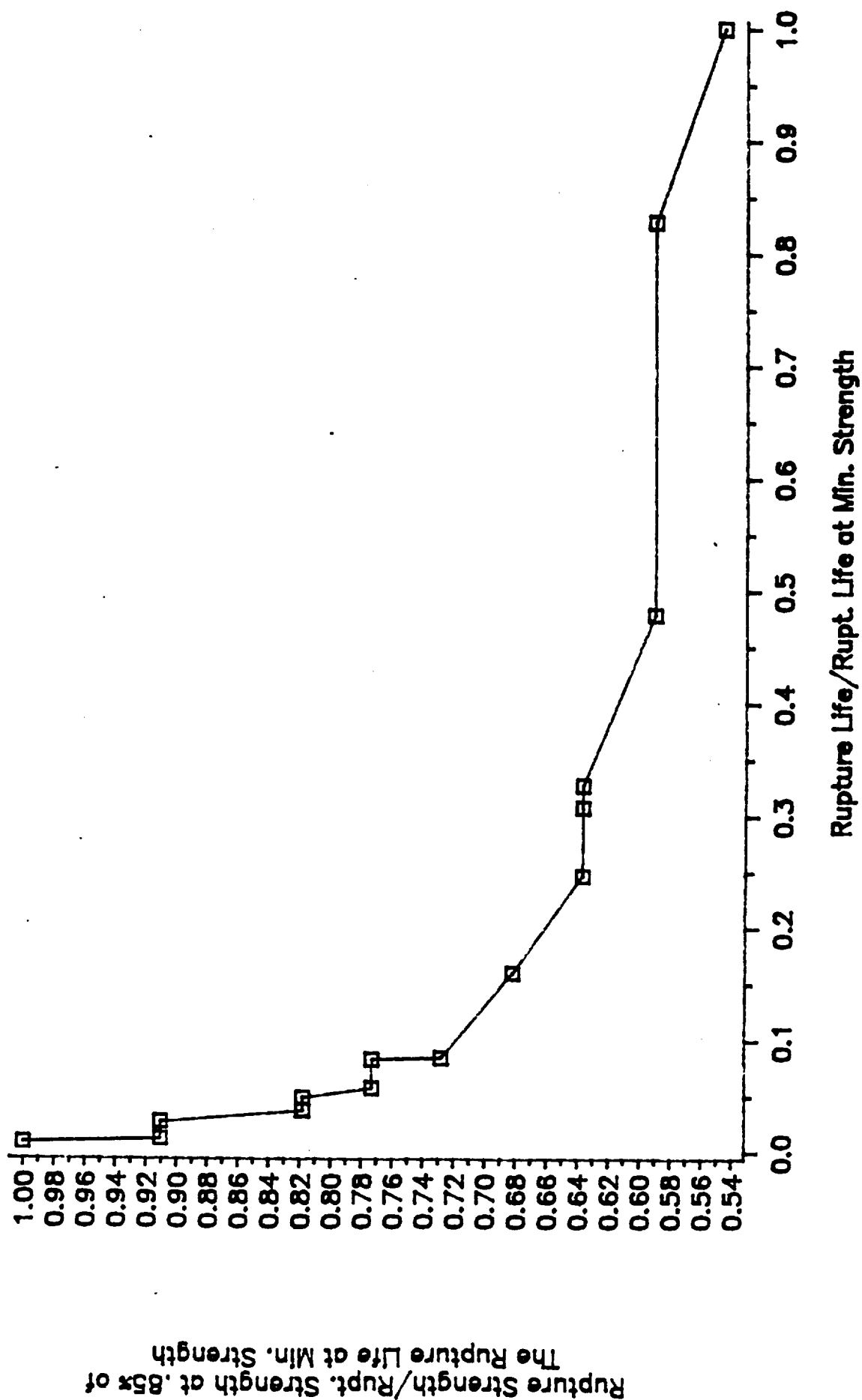
TEST TEMP. = 1400 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TUNGSTEN FIBER ST300



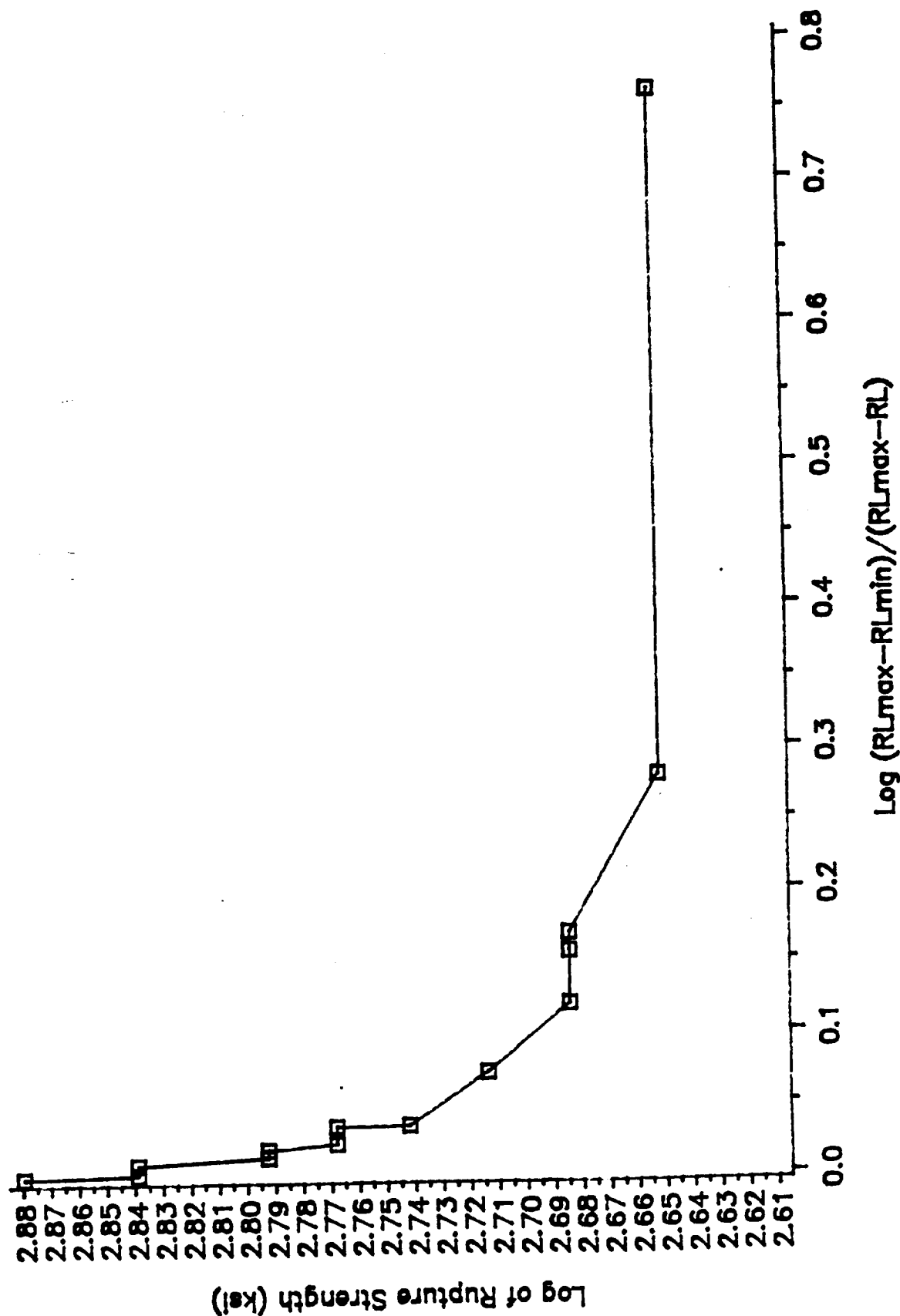
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EFFECT OF TIME ON RUPTURE STRENGTH FOR TNST300



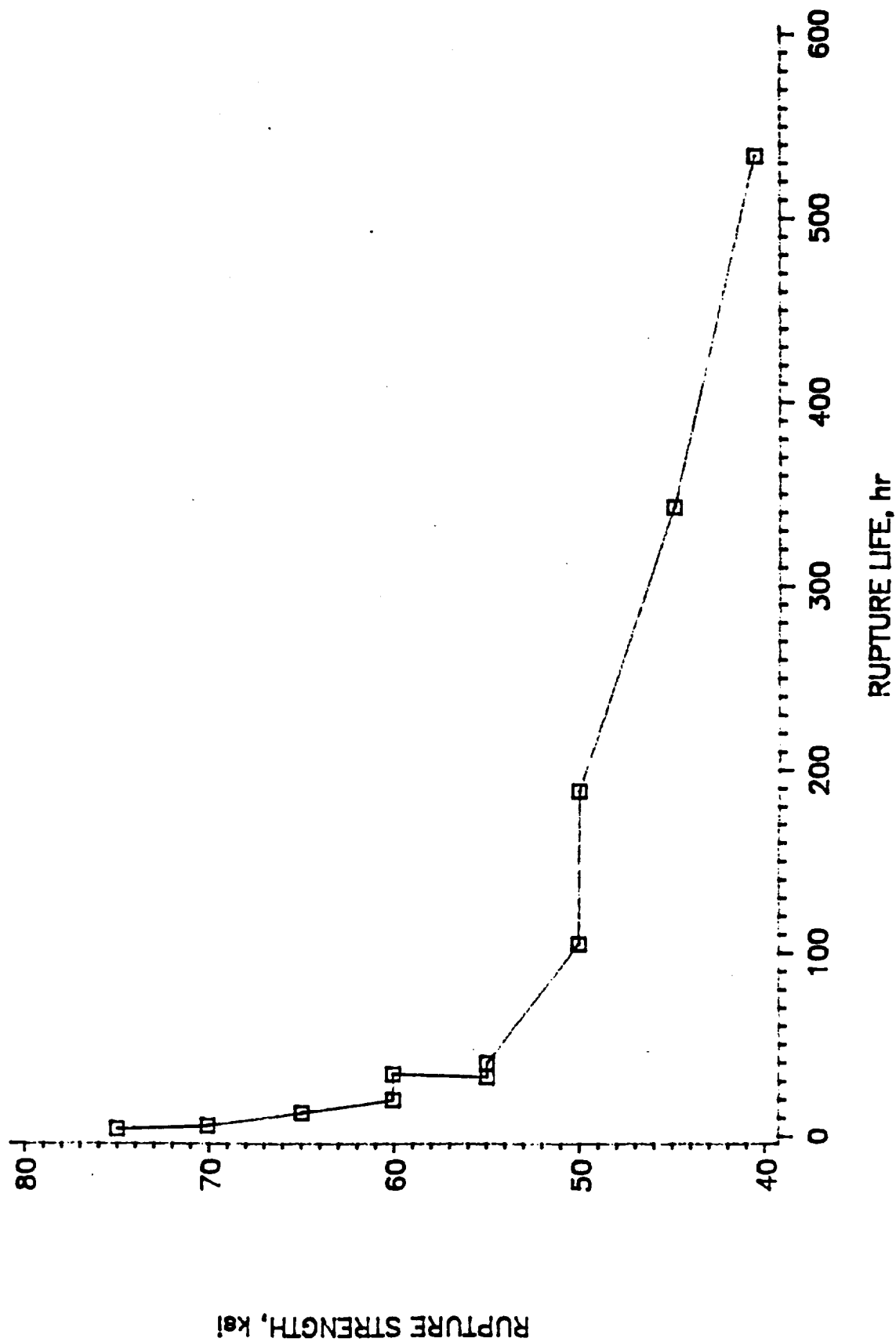
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EFFECT OF TIME ON RUPTURE STRENGTH FOR TNST300



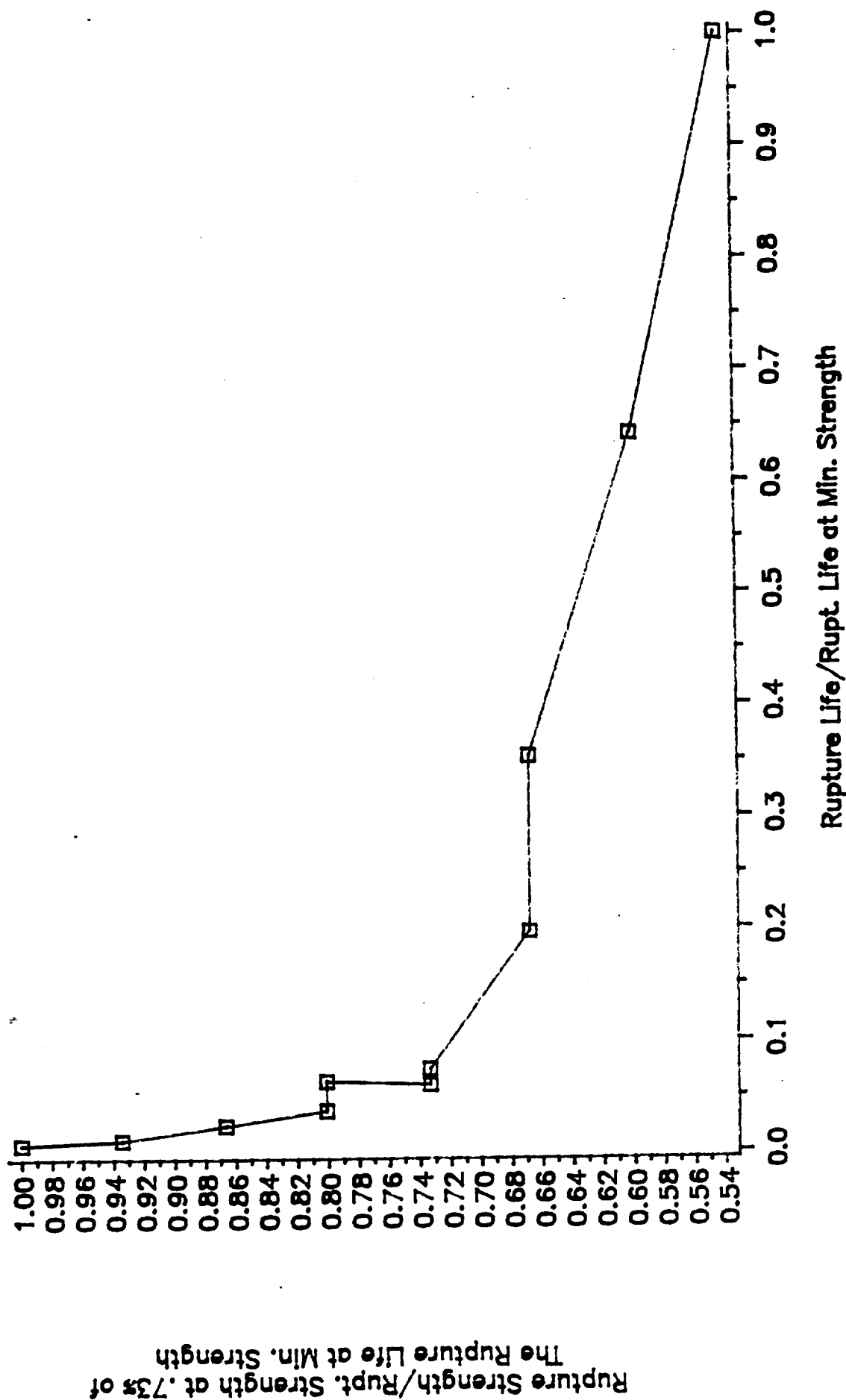
TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TUNGSTEN FIBER ST300



TEST TEMP. = 1500 F

EFFECT OF TIME ON RUPTURE STRENGTH FOR TNST300



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13. ABSTRACT (Maximum 200 words) This report presents the results of a second year effort of a research program conducted for NASA-LeRC by the University of Texas at San Antonio (UTSA). The research included development of methodology that provides probabilistic lifetime strength of aerospace materials via computational simulation. A probabilistic phenomenological constitutive relationship, in the form of a randomized multifactor interaction equation, is postulated for strength degradation of structural components of aerospace propulsion systems subjected to a number of effects or primitive variables. These primitive variables often originate in the environment and may include stress from loading, temperature, chemical or radiation attack. Time may also interact with them, producing creep and fatigue. In most cases, strength is reduced as a result. This multifactor interaction constitutive equation is included in the computer program, PROMISS. Also included in the research is the development of methodology to calibrate the above-described constitutive equation using actual experimental materials data together with a multiple linear regression of that data, thereby predicting values for the empirical material constants for each effect or primitive variable. This methodology is included in the computer program, PROMISC. Actual experimental materials data were obtained from the open literature for a number of nickel-base superalloys and a few metal-matrix materials, materials typically of interest for aerospace propulsion system components.				
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TEST TEMP. = 1500 K

EFFECT OF TIME ON RUPTURE STRENGTH FOR TNST300

